NASA Contractor Report 3880



# Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

*Program Review*



Boeing Commercial Airplane Company

CONTRACT NAS1-15325
MARCH 1986



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# Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project

*Program Review*

Boeing Commercial Airplane Company
*Seattle, Washington*

Prepared for
Langley Research Center
under Contract NAS1-15325

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

**1986**

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# 1.0 SUMMARY

This report summarizes the Integrated Application of Active Controls (IAAC) Technology to an advanced subsonic transport project. This project was established as one element of the NASA/Boeing Energy Efficient Transport Technology Program. The IAAC Project was undertaken to:

- Produce a credible (indepth) assessment of the benefits associated with the design of a commercial transport airplane using Active Controls Technology (ACT).
- Identify technical risk areas and recommend test and development programs.
- Implement selected test and development programs.

The first two objectives and part of the third were achieved prior to the NASA decision to eliminate further project funding. The performance assessment showed that incorporating ACT into an airplane designed to fly approximately 200 passengers approximately 2,000 nmi could yield block fuel savings from 6% to 10% at the design range. Based on a fuel cost of $0.26/liter ($1.00/gal), these performance improvements were estimated to yield a 25% incremental rate of return on the additional investment in the ACT airplane compared to a conventional airplane designed to operate over the same mission.

The principal risks associated with incorporating these active control functions into a commercial airplane are those involved with the ACT system implementation. In particular, when the flight safety of the airplane is dependent on the ACT systems, those systems must be as reliable as other flight-critical systems or components, and exhibit availability suitable for a commercial transport. The Test and Evaluation phase of the IAAC Project focused on the design, fabrication, and test of an ACT system, i.e. the Test ACT System, which implemented pitch axis fly-by-wire, pitch axis augmentation, and wing load alleviation. The Test ACT System was built to be flight worthy and was planned to be experimentally flown on the 757. The system was installed in the Boeing Digital Avionics Flight Controls Laboratory (DAFCL), and open loop hardware and software tests were completed there. The testing was truncated in

favor of examining a direct drive valve (DDV) actuation concept when it became clear that the project would not continue into a flight test phase.

A DDV was installed in a test fixture in the DAFCL, the Test ACT System electronics were modified to interface with the DDV, and a limited amount of testing was accomplished. The results show that the concept has promise, but needs additional development before it is suitable for a commercial application.

The IAAC Project has shown that ACT could be beneficially incorporated into a commercial transport airplane if adequate research were conducted to provide technical confidence sufficient for committment. During the project, a candidate pitch axis ACT system was selected, designed, and built to meet the reliability requirements considered necessary for a commercial ACT application. The test was truncated, but, based on the results achieved, there appears to be no fundamental reason(s) that would preclude the commercial application of ACT, assuming an appropriate development effort.

It is recommended that NASA resume support to the development of advanced flight control concepts suitable for application to commercial transport airplanes, as was being done under the IAAC Project. Advanced systems for these commercial flight critical applications must meet stringent reliability/availability requirements that are beyond those achievable by current military systems. NASA should continue to sponsor and/or participate in advanced flight control developments that can contribute to the advancement of, or maintenance of, United States world leadership in commercial aviation.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND

Why is ACT important? It is one of several technologies that have the potential of significantly reducing the fuel required by the world's air carriers. Free-world air carriers consumed about 1.5M barrels of jet fuel/day in 1975. This was admittedly a small part of the free-world's total petroleum consumption of approximately 50.0M barrels/day. However, commercial jet aviation is a highly visible, high-technology, fuel-using industry that is potentially more amenable to an infusion of new technology than many other petroleum-using industries in today's world. These considerations, and a very real concern with the stability of petroleum supplies to the free world, provided the backdrop for the United States Senate in early 1975.

In response to a request by Senators Frank E. Moss and Barry Goldwater in January 1975, James C. Fletcher, then NASA Administrator, established a task force of government scientists and engineers to draw up a comprehensive program plan for developing aeronautical fuel-conservation technology. The task force report was submitted to the Senate Committee on Aeronautical and Space Sciences in September 1975. A summary of that report was published in AIAA Astronautics & Aeronautics in February 1976 (ref. 1). The task force defined six major programs that could lead to fuel conservation in commercial air transportation. The six programs were grouped under the three categories of propulsion, aerodynamics, and structures. The aerodynamic group consisted of the Laminar Flow Control and Energy Efficient Transport (EET) programs. The EET program included evolutionary improvement of aerodynamic design, including work on winglets and drag cleanup, and development of ACT.

ACT has the potential of improvement in two of the three technical areas that affect airplane fuel efficiency: aerodynamics and structure. ACT is a design concept to improve airplane performance by relying upon the flight control system to augment the airplane's stability and reduce aerodynamic trim drag (improved aerodynamic efficiency), while reducing structural loads (reduced airplane weight). Airplane stability is augmented to allow a smaller empennage and aft center of gravity, resulting in reduced profile and trim drag and empennage weight. Structural weight can also be reduced by activating control surfaces to reduce maneuvering and gust

loads, to reduce fatigue loads due to turbulence, and to dampen structural modes that contribute to flutter instability.

Extensive research and testing in these technologies was carried out through independent NASA- and industry-sponsored programs. Although results were encouraging, showing potential performance improvements and demonstrating the working elements of various active controls systems, the data in Figure 1 shows that at the beginning of the IAAC Project, commercial operational experience existed in only two aspects of ACT: augmented stability and ride control. Typically, these applications were not integrated, but had been individually designed and implemented. In most cases these limited applications were made either to overcome an unanticipated difficulty or to add capability to the commercial airplane. A significant body of evidence strongly suggested that an integrated application of ACT would yield the most significant performance improvement. Thus, the various ACT functions should not be considered independently, but must be designed in concert with the airplane design to provide the optimum performance improvement and preserve acceptable airplane characteristics. This had not been accomplished prior to 1979, even in research activities. Advances in solid-state electronics promised improvement in critical system reliability and reductions in system cost. However, little effort had been expended toward clear identification of overall benefits, cost of ownership, and technical risks associated with a future major application of ACT.

To meet the EET program objective of expediting the application of ACT to commercial transports, the factors currently impeding such an application had to be identified, and a plan to reduce or eliminate them had to be developed. The IAAC Project was undertaken to accomplish this.

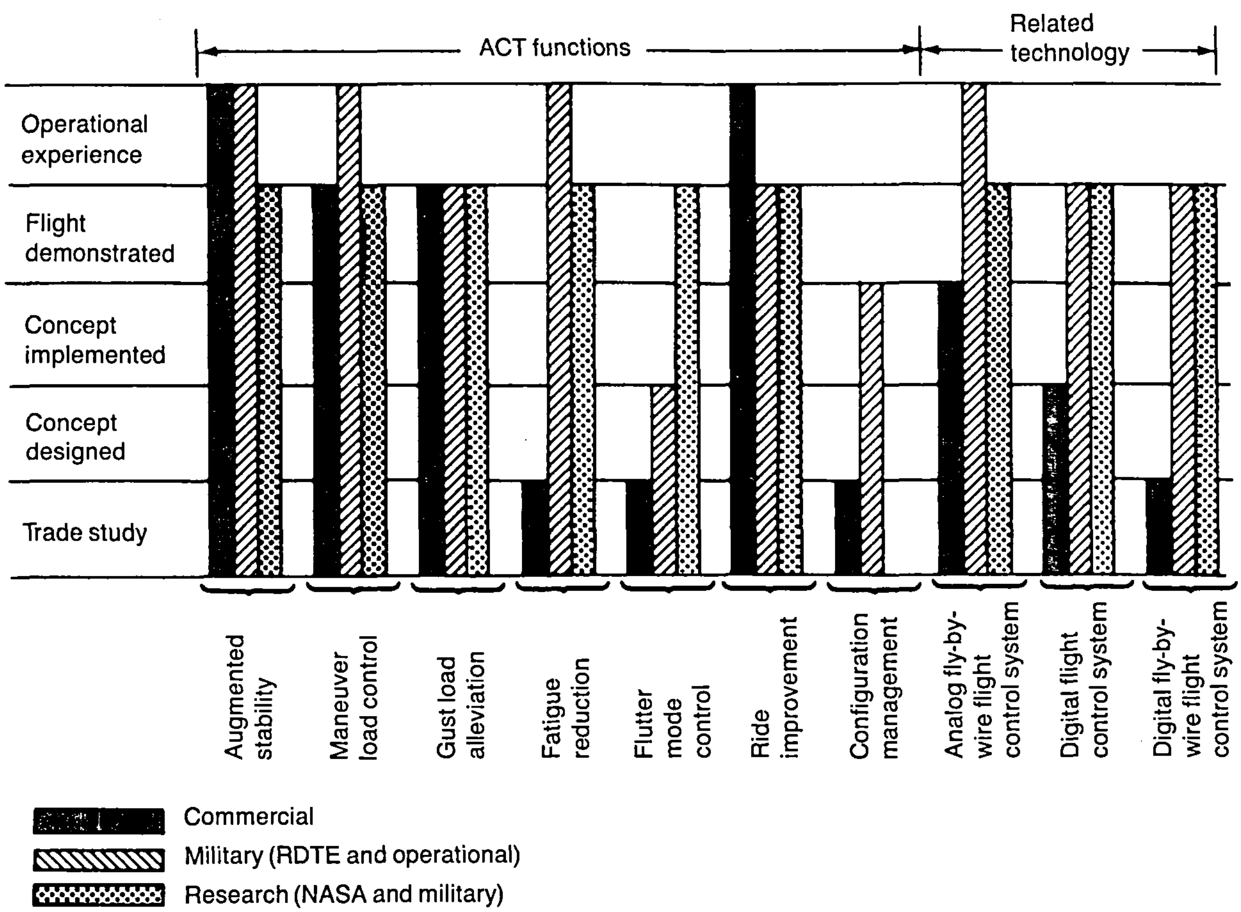



*Figure 1. Active Control Technology State of the Art (1979)*

## 2.2 PROJECT PLAN

If the potential benefits were so large, what blocked the full incorporation of ACT in commercial transports? Such applications would rely on flight-critical systems to provide the ACT functions. The term "flight-critical" describes any function whose loss can result in an immediate, unconditional flight safety hazard. All control system elements providing such functions must be operating for continued safe flight. Before the airframe manufacturer, operating airline industries, and the regulatory agencies would become receptive to commercial transport designs that were truly dependent upon ACT systems, three important questions had to be answered:

1. When implemented to the fullest extent during preliminary design of a practical transport, does ACT offer benefit potential sufficient to warrant its development to a "ready for commitment" status?

2. If the benefit potential, defined in answer to the first question, is sufficiently attractive, what analytical and design methods, and laboratory and flight evaluation developments are required to bring ACT to commitment readiness?

3. After adequate development, are system reliability and maintainability characteristics technically and economically acceptable?

The IAAC Project plan (ref. 2 and fig. 2) was designed to address these questions. The plan consisted of three major elements:

1. Configuration/ACT-System Design and Evaluation (fig. 3)

   The configuration element provided a credible assessment of ACT benefits and defined related development requirements in response to the first two questions noted above. This element was pursued using state-of-the-art implementation of the ACT control systems, so that the benefit assessment did not depend upon technical breakthroughs.

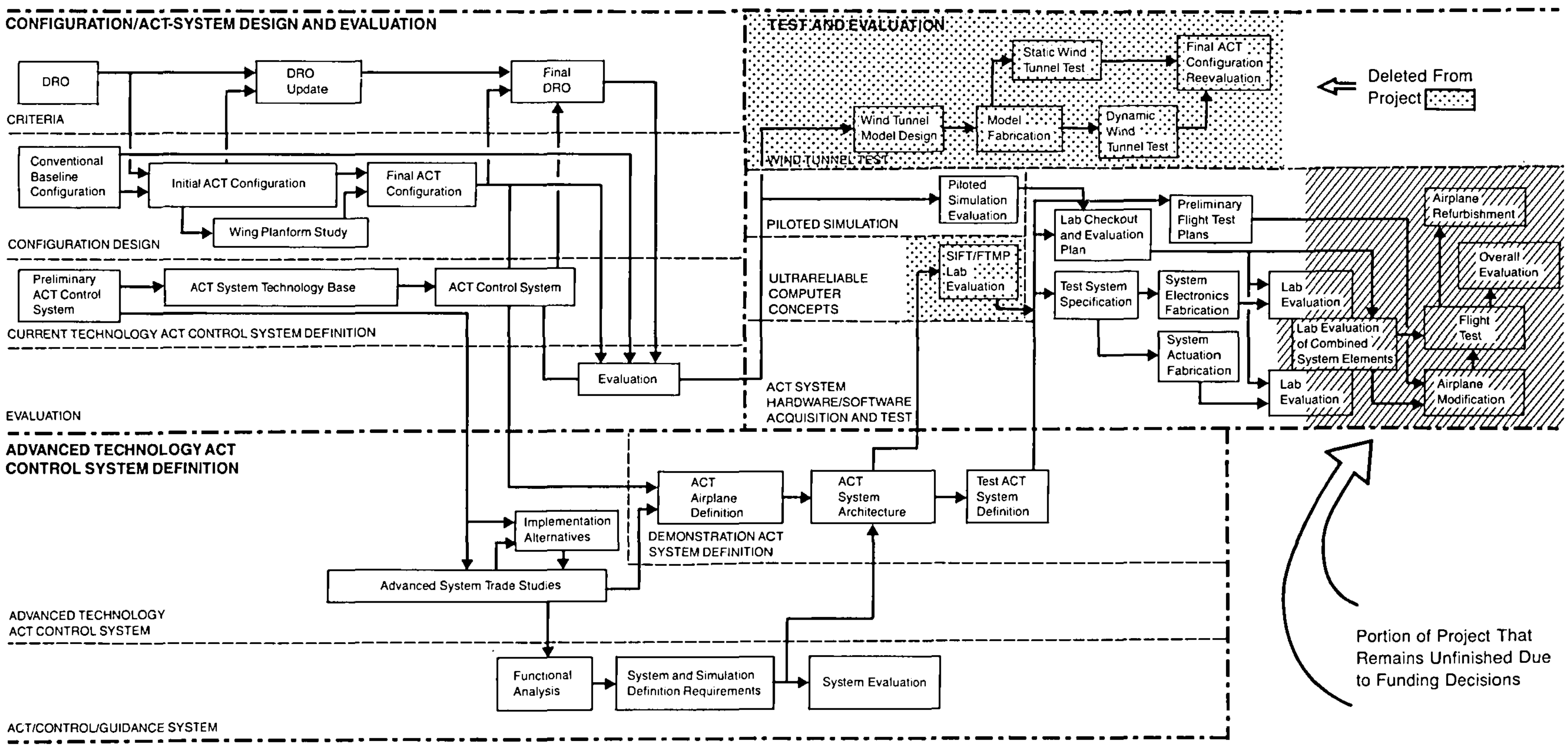



*Figure 2. IAAC ACT Development Program*

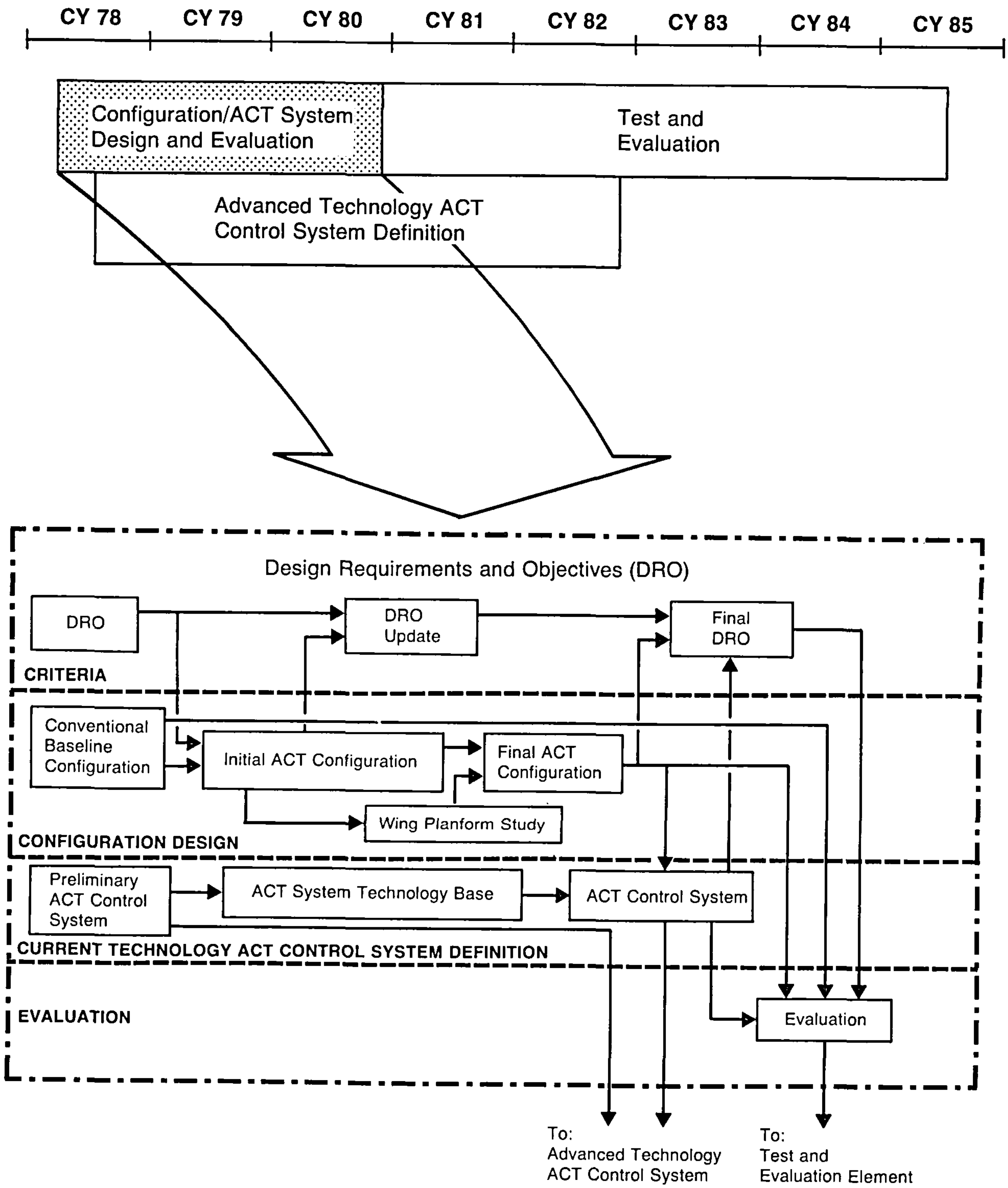



*Figure 3. Configuration/ACT-System Design and Evaluation Element*

2. Advanced Technology ACT Control System (fig. 4)

This element identified state-of-the-art technology advancements applicable to optimized implementation of ACT system functions and integration of ACT with guidance and control systems avionics. This element was pursued in parallel with the configuration element, so that the final benefit evaluation included a study of the advantages of technology advancement predictions.

3. Test and Evaluation (fig. 5)

This element was devoted to laboratory verification of ACT systems development to provide a positive answer to the final question posed above. It was pursued after a sufficiently positive potential benefit resulted from the assessment effort described for the configuration element. State-of-the-art system elements and technology advancements identified during the IAAC Project were considered during the design of a flight-worthy ACT and pitch axis FBW control system. A test system was built and tested in Boeing laboratories. After the project was underway, it was decided that the wind tunnel test work would best be accomplished under industry sponsorship. The final tasks, dealing with integrated system testing, airplane modification, and flight testing, were never accomplished because the project was terminated during the laboratory test phase.

Figure 6 shows the actual time relationship of the several phases of the IAAC Project.

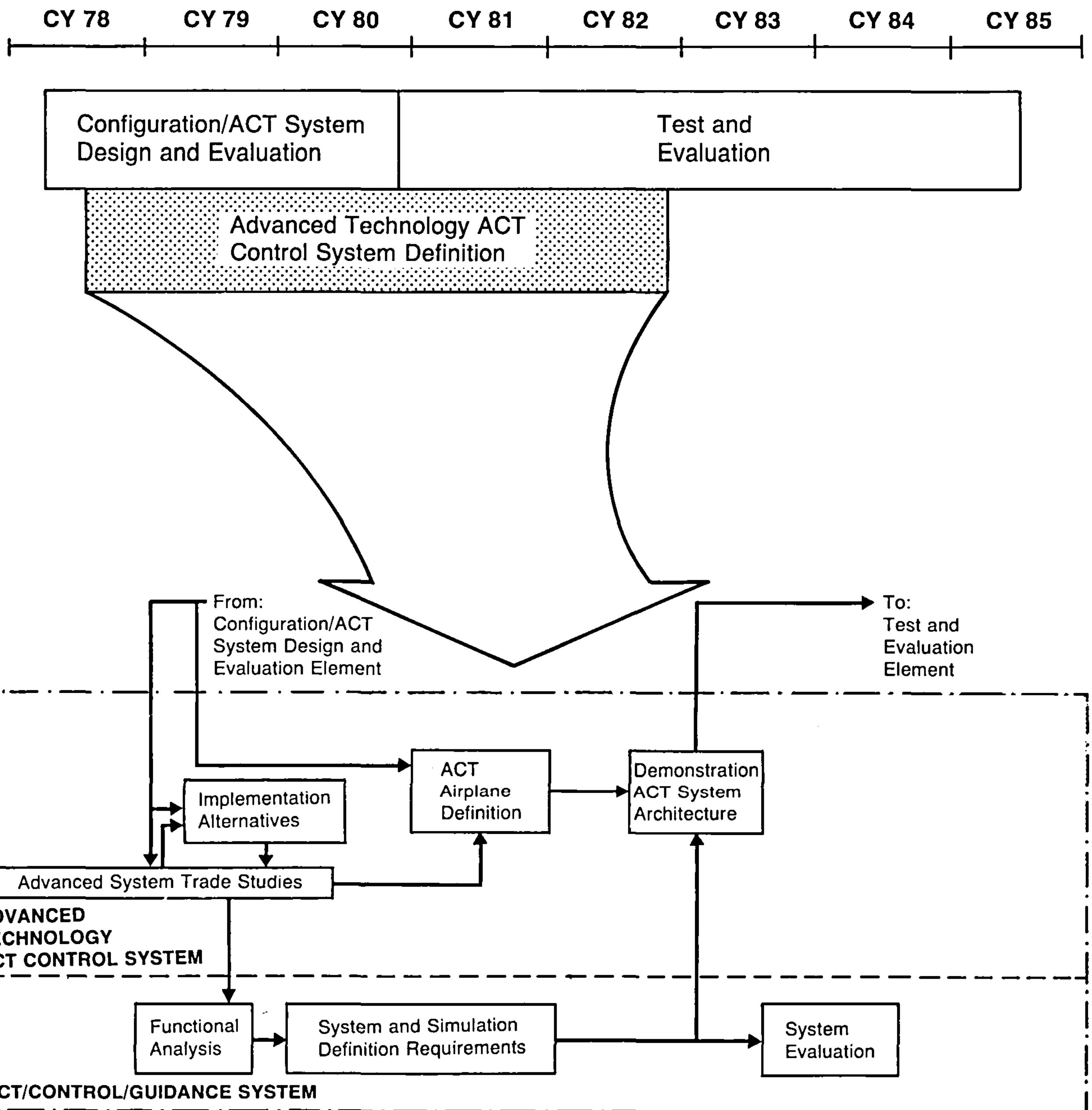



*Figure 4. Advanced Technology ACT Control System Definition Element*

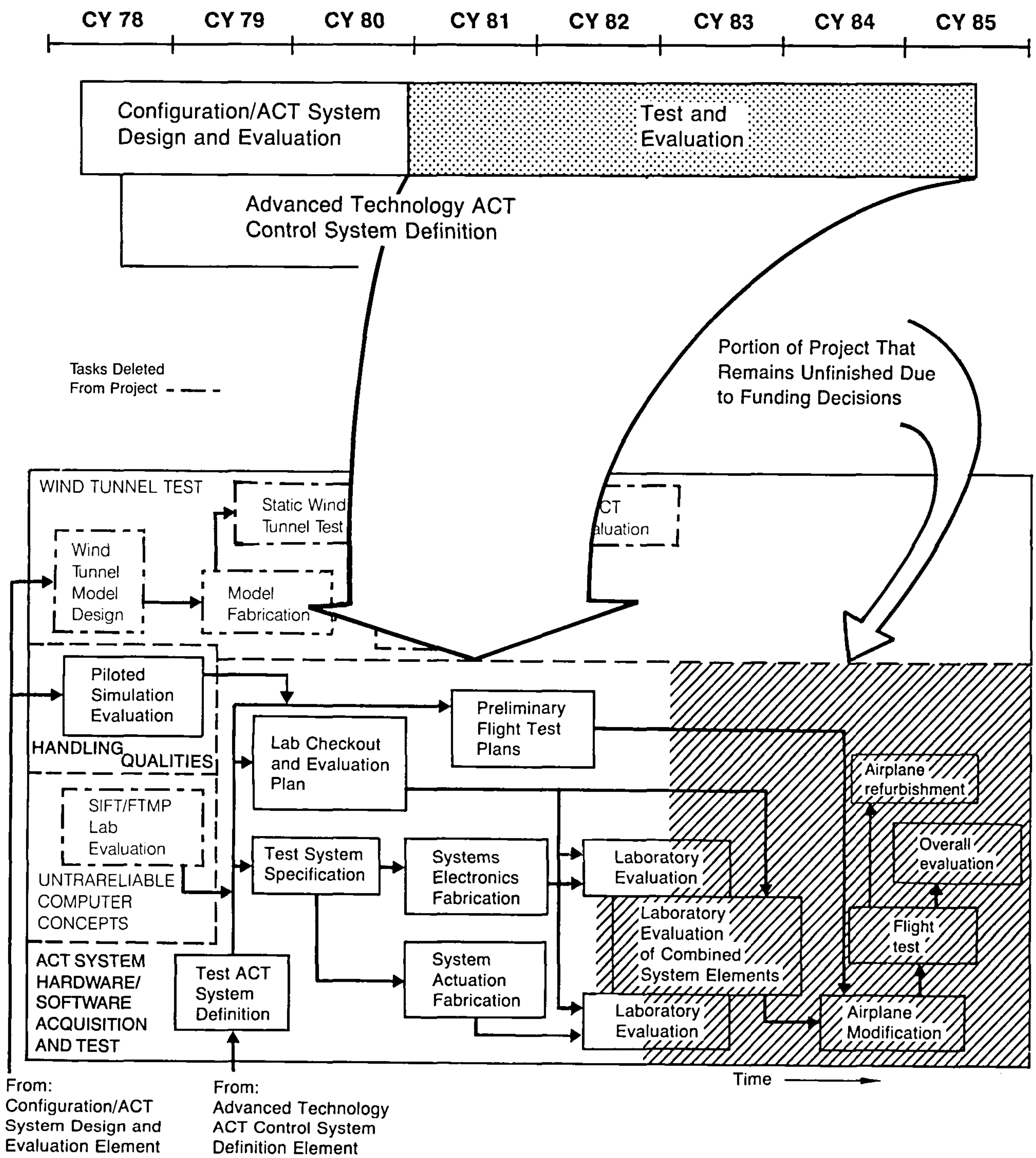



*Figure 5. Test and Evaluation Element*

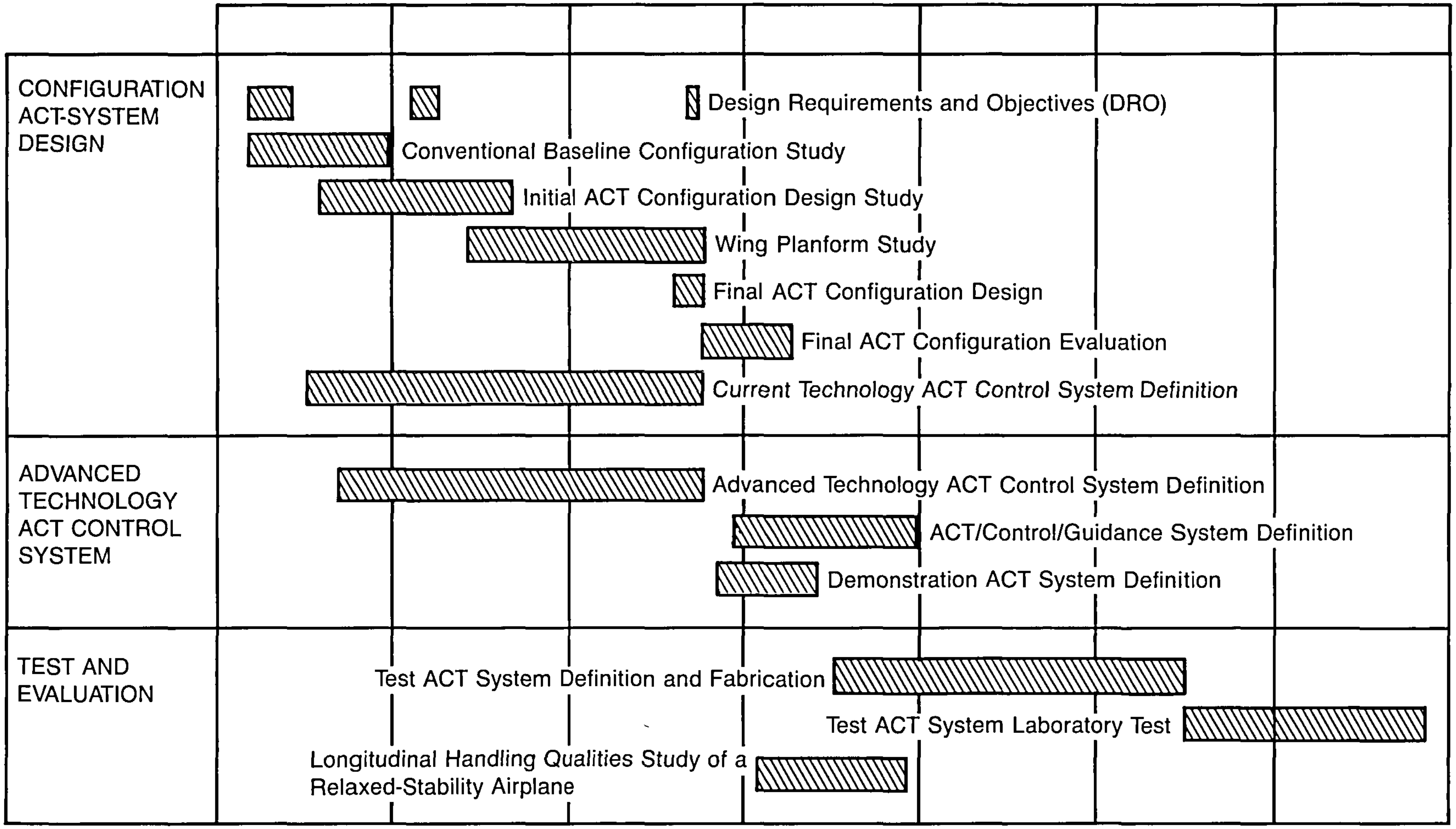



*Figure 6. Integrated Application of Active Controls Technology Program*

## 3.0 ABBREVIATIONS

| | |
|---|---|
| AAL | angle of attack limiter |
| ACC | Active Controls Computer |
| ACL | accelerometer |
| ACT | Active Controls Technology |
| AED | ALGOL Extended for Design |
| ALGOL | Algorithmic Language |
| cg | center of gravity |
| DADC | Digital Air Data Computer |
| DAFCL | Digital Avionics Flight Controls Laboratory |
| DDV | direct drive valve |
| deg | degree; degree of arc |
| DRO | design requirements and objectives |
| EET | Energy Efficient Transport |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulations |
| FBW | fly by wire |
| FCC | Flight Control Computer |

## 3.0 ABBREVIATIONS (Continued)

| | |
|---|---|
| FMC | flutter mode control |
| FTMP | fault tolerant multiprocessor |
| GLA | gust-load alleviation |
| IAAC | Integrated Application of Active Controls |
| IRS | Inertial Reference System |
| km | kilometer |
| LAS | lateral/directional augmented stability |
| MAC | mean aerodynamic chord |
| MLC | maneuver-load control |
| $M_{MO}$ | maximum operating Mach number |
| nmi | nautical mile |
| NASA | National Aeronautical and Space Administration |
| ROI | return on investment |
| SIFT | software-implemented fault tolerance |
| $V_D/M_D$ | design dive speed |
| $V_{MO}$ | maximum operating airspeed |
| WLA | wing-load alleviation |

## 4.0 IAAC PROJECT OBJECTIVES

The IAAC Project objectives were to: 1) Determine the potential performance and economic benefits of incorporating ACT in a commercial transport airplane; 2) Identify the technical risk areas that preclude application of ACT to new commercial airplanes, and identify those elements of research and development work that should be undertaken immediately to make ACT ready for incorporation on a new generation of commercial transport airplanes; and 3) Pursue the risk-reducing research and development as far as possible within the funding constraints of the project. In order for the results of this project to contribute to the future incorporation of ACT into a commercial airplane, it was necessary for the predicted performance benefits to be credible, the predicted cost of ownership to be acceptable from an operating airline point of view, and for the technical and economic risks to be commensurate with new commercial airplane programs. The IAAC Project results met these objectives, although due to funding limitations the risk reduction work was not completed.

The principal purpose of this project was to remove existing deterrents to a major commercial application of ACT. A number of ACT design studies had been applied to various airplane missions but, with few exceptions, results of these studies lacked the depth, thoroughness, and credentials (commercial experience and data base) required for a commitment to a commercial development program. The <u>first objective</u> of this program was to produce an indepth assessment of the benefit (both performance and economics) associated with a major ACT application to a commercial transport. This assessment was based upon major future development of a new airplane, as opposed to addition of ACT to an existing airplane to produce a derivative.

ACT's maximum benefit will be achieved when the airplane configuration is influenced by the use of all beneficial ACT functions. Some of these functions will likely be incorporated as flight-critical systems. A major obstacle to such a broad application of active controls is the perceived risk of relying upon nonmechanical, flight-critical control systems. A necessary condition for the inclusion of major ACT functions in a new airplane design is that the management of the commercial airframe manufacturer and the airlines, as well as the technical community, weighs the risk of including the new technology and determines that the risk is acceptable and the benefits can be obtained cost-effectively. Thus, the <u>second objective</u> of the program was to identify

the risk areas and to outline the development program necessary to bring ACT to commercial commitment-readiness. The third objective of the program was to reduce the risks associated with the use of ACT through the design, laboratory test, and flight test of a Test ACT system. Significant reduction in the identified risk areas will result only from hands-on experience with the design and testing of critical, commercial quality ACT systems. The system was to be designed to the redundancy levels that would be required for certification in a commercial transport airplane. This work proceeded through design, build, and the beginning of laboratory test.

## 4.1 BENEFITS ASSESSMENT

The determination of the benefits of ACT required a baseline airplane with appropriate data that could be used as a measure of the improvements accomplished with the inclusion of ACT. The NASA/Boeing IAAC Project plan (ref. 2) was to use a Boeing 7X7 airplane configuration that, at the beginning of the IAAC project, was under development within the New Product Development organization of the Boeing Commercial Airplane Company, as this baseline airplane.

In order to identify the importance of airplane configuration effects on performance and economics, the benefits assessment plan introduced the ACT functions into the airplane design in a series of steps. At each step, the practical aspects of the airplane configuration were to be maintained in order to produce the clearest possible assessment of the benefits. This meant that all of the airplane configurations had to have the same passenger/payload capability, essentially the same range/field-length capability, and the same potential for options such as space for a lower-deck pallet door. In addition, the technical state of the art in such items as the degree of incorporation of composites, or the main landing gear design, had to be maintained. These constraints were introduced and maintained to ensure that the project results would yield the desired benefits assessment quality.

Furthermore, the ACT system implementation associated with performance and economic assessment had to be based upon current technology. This ground rule allowed the airplane design to proceed without depending upon a new invention, and was viewed as a conservative factor in the benefit determination. Any new technology that would improve the ACT systems through weight reduction or improved reliability

would lead to even greater benefits. Therefore, ignoring such potential developments for this part of the work was a conservative approach.

The first ACT Airplane configuration, and associated benefits assessment, was developed by eliminating the airframe aerodynamic stability requirements and resizing the empennage accordingly, while maintaining the cruise wing aerodynamics (wing shape at the cruise loading). This airplane configuration was called the Initial ACT Airplane configuration.

The second major step in benefits assessment was to determine the effect of the wing planform on the ACT Airplane performance, select a planform that appeared to be near optimum for the ACT Airplane, then resize the airplane to the baseline airplane mission. This resulted in the Final ACT configuration and yielded the maximum fuel saving from the application of active controls.

## 4.2 RISK ASSESSMENT

Early in the program it was observed that there were two main areas of potential risk resulting from the active controls airplane development:

1. The risk involved in operating an unstable airframe, with its associated dependency upon a critical flight control system.

2. The present and foreseen impact of an ACT Airplane (incorporating active controls and critical flight control electronics) upon air transport facilities and the operating network.

These risks, and system aspects associated with them, were the subjects of two of the major elements of the project. These were the Current and Advanced Technology Control System Definition Study and the ACT/Control/Guidance System Study. In addition to the system questions, there was also the question of the handling-quality characteristics of an ACT Airplane, particularly with reference to the projected flight test of an active controls system in the still experimental stages of ACT development. To that end, a handling qualities study and piloted simulation experiment was included in the IAAC program in the second and third program elements.

### 4.3 RISK REDUCTION

The test and evaluation element of the IAAC program was designed to reduce risks through the process of designing, building, and testing the several elements of an ACT system. The testing was originally envisioned to include flight tests, as reflected in Figure 5. The figure is the diagram of that planned program element, showing those parts of it that were completed within the limits of the program funds allotted.

## 5.0 TECHNICAL RESULTS

The IAAC Project simultaneously addressed both the airplane design issues and the ACT system design issues. The results of the airplane design studies, hardware/software design and build, and the laboratory investigations are all briefly presented in this section. There is a separate section devoted to each of the primary subjects of investigation.

The first major subsection (5.1) addresses ACT airplane performance and economics. The selection of the Conventional Baseline Airplane, the Initial ACT Airplane design, the Wing Planform Study results, and the selection and analysis of the Final ACT Airplane are all treated in Section 5.1. The Current Technology ACT System, used in the determination of the performance of the ACT airplanes, and the economic analyses; the Advanced Technology ACT Systems; the longitudinal handling qualities of the ACT airplane; and the Test ACT System are all treated in the second major subsection (5.2).

Each one of the three IAAC Project objectives described in Section 4.0 was served by more than one of the IAAC Project elements treated below. This section summarizes the results of this design/analysis/test work and the extent to which it reduced risks in applying active controls to a commercial transport airplane. A reading of this section and the "Conclusions and Recommendations" section (7.0) may be required to fully understand the relationship among the individual project elements and the manner in which they respond to the three major project objectives.

### 5.1 ACT AIRPLANE PERFORMANCE AND ECONOMICS

Identification of the benefits that would result from including ACT in the design of a new airplane clearly requires that a conventional airplane (including no significant ACT applications and designed for the same mission) be available as a reference for both performance and economics. The effects of including ACT will depend upon the particular airplane configuration and the mission it is being used for. Therefore, before proceeding with the determination of the effects of ACT on the performance and economics of a commercial jet transport, an appropriate mission and an airplane configuration must be selected.

United States air carriers consumed about 10 billion gal of jet fuel annually in 1977 and 1978. This was about 44% of the 1.5 million barrels/day used by the free-world carriers. U.S. domestic carriers used about 83% of the U.S. total. U.S. domestic trunk air carriers used about 7.5 billion gal annually. As this work was accomplished under NASA sponsorship with the objective of advancing national interest, an airplane in extensive use in the domestic fleet would make the best reference. The next questions, then, are what airplane fleet type, operating for what mission, would offer the greatest leverage on fuel savings.

The data of Reference 3 show that the 727 domestic fleet used approximately 2.5 billion gal annually. That one airplane type (727), operating over an average stage length of about 500 mi, utilized one-half as much fuel as all other domestic airplane types combined. If it were possible to make a fleet substitution for one airplane type, substituting an ACT airplane for the 727 would provide the greatest leverage on fuel savings. This is partly due to the large number of 727 airplanes operating domestically.

It should be noted that although the 727 is operated at stage lengths (the distance flown between a takeoff and landing) up to nearly 2000 nmi, on average it operates at 500 nmi. The question could be asked, "Why not design an ACT airplane with a range of 500 nmi?" Such an airplane would be smaller and lighter, and would probably use less fuel over the shorter design range distances. However, it would sacrifice a very important consideration, which is operational flexibility. Therefore, even though the 727 is operated at relatively short stage lengths, the target mission for the IAAC project was selected with a design range of approximately 1500 to 2000 nmi, in order to retain an operational flexibility similar to that of the 727.

The selected target conventional airplane characteristics and design mission are summarized in Table 1. The project objective to identify the benefits of ACT required that the ACT airplanes perform the design mission as well as the Conventional Baseline Airplane. If the ACT airplane turns out to be better in some aspect of mission performance, e.g. range out of Denver on a hot day, it must be achieved at no additional cost. This included consideration of noise, flying qualities, and technology in general.

*Table 1. Target Conventional Airplane Characteristics*

| | |
|---|---|
| Configuration | |
| • Passengers | 150 to 200 |
| • Engines | 2 or 3 |
| Design mission | |
| • Cruise Mach | 0.80 |
| • Range | 1500 to 2000 nmi |
| • Takeoff field length | 8,000-ft maximum |
| • Approach speed | 135 kn |
| • Noise | Current commercial conventional transport practice |
| • Flying qualities | Current commercial conventional transport practice |
| Technology | |
| Airplane technology (aerodynamic, structural, propulsion, etc.) to be consistent with current commercial conventional transport practice. | |

### 5.1.1 CONVENTIONAL BASELINE AIRPLANE

The Conventional Baseline Airplane configuration was to provide the technical and economic base for the ACT airplane design work as described above. A second function of the baseline was to provide calibration data for the preliminary design tools and methods to be used in the ACT airplane design. This second function could only be accomplished if the baseline configuration was defined in sufficient technical detail to allow comparison of the data with a "redesign" of the airplane using the tools to be used in the IAAC Project. At the time this decision was being considered, the 7X7 was being designed within the Boeing Commercial Airplane Company New Product Development organization. At the time the Conventional Baseline Airplane configuration was selected, the 7X7 configuration was a medium-range, twin-engine, T-tail airplane with well-documented analytical and test data. This airplane, which met all of the previously discussed criteria, later evolved into the 767 production airplane.

The selected Conventional Baseline Airplane configuration is shown in Figure 7, and its characteristics and performance are summarized in Table 2. The airplane configuration has an 8.71 aspect ratio, 31.5-deg swept wing; a T-tail empennage; and two wing-mounted CF6-6D2 engines. It is designed to carry just under 200 passengers over a still-air range of approximately 2000 nmi. The fuselage is nearly circular, with a double lobe; the passenger section has a two-aisle, seven-abreast layout; and the lower lobe has volume for 22 LD-2 or 11 LD-3 cargo containers and bulk cargo. Operationally, passenger and cargo loading, servicing provisions, taxi and takeoff speeds, and field length characteristics are all compatible with accepted airline and regulatory provisions.

The Conventional Baseline Airplane configuration principally uses conventional aluminum structure with selected applications of advanced aluminum alloys, and graphite-epoxy secondary structure. The airplane uses modern systems, including advanced guidance, navigation, and controls, that emphasize application of digital electronics and advanced cathode ray tube displays. Further characteristics and performance details are contained in the Conventional Baseline Configuration Study Final Report, Reference 4.

Geometry:

| | | | |
|---|---|---|---|
| Body cross section, m (in) | | | |
| Shape | Vertical double lobe | | |
| Maximum width | 5.292 (198.00) | | |
| Maximum height | 5.410 (213.00) | | |
| Landing gear | Nose | Main | |
| Type | Dual | Truck | |
| Location, m (in) | 6.896 (271.50) | 56% MAC | |
| Spacing, m (in) | 0.609 (24) | 1.143 x 1.422 (45 x 56) | |
| Tire size, m | 0.939 x 0.330 -0.406 | 1.092 x 0.393 - 0.508 | |
| (in) | (37 x 13-16) | (43 x 15.5-20) | |
| Oleo stroke, m (in) | 0.381 (15) | 0.457 (18) | |
| Aerodynamic surfaces | Wing | Vertical tail | Horizontal tail |
| Area, $m^2$ ($ft^2$) | 256.3 (2759)[a] | 57.4 (618) | 57.6 (620) |
| Aspect ratio | 8.71[a] | 0.67 | 4.00 |
| Taper ratio | 0.267[a] | 0.700 | 0.400 |
| Sweep at c/4, deg | 31.5[a] | 55.0 | 35.0 |
| Incidence, SOB, deg | 3.8[a] | – | – |
| Dihedral, deg | 6.0[a] | – | – |
| Root t/c, percent | 15.1 | 12.0 | 11.0 |
| Tip t/c, percent | 10.3 | 12.0 | 9.0 |
| Root chord, m (in) | 8.567 (337.30)[a] | 10.888 (428.69) | 5.421 (213.45) |
| Tip chord, m (in) | 2.286 (90.00)[a] | 7.622 (300.08) | 2.168 (85.37) |
| MAC, m (in) | 6.031 (237.47)[a] | 9.351 (368.17) | 4.027 (158.55) |
| Span, m (in) | 47.244 (1860.00)[a] | 6.201 (244.14) | 15.179 (597.61) |
| Tail arm, m (in) | – | 19.972 (786.30) | 27.134 (1068.30) |
| Tail arm, coefficient[b] | – | 0.088 | 0.942 |

Engine toe-in angle—1 deg to a BBL
Nacelle incidence—2.625 deg to a BWL
Wing upper surface at side of body rib at WL 4.940m (194.5 in)

[a]Trapezoid geometry quoted: aero reference area = 275.1 $m^2$ (2961 $ft^2$)

[b]Based on aero reference area

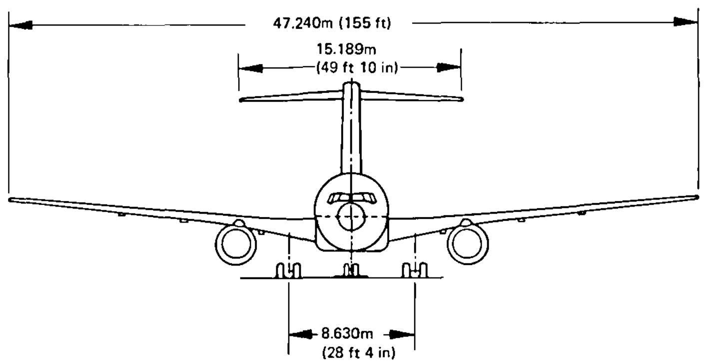
| Passenger accommodations: | Passengers | Abreast | Pitch |
|---|---|---|---|
| First class | 18 | 6 | 0.965m (38 in) |
| Tourist | 179 | 7 | 0.864m (34 in) |

| Cargo and baggage, $m^3$ ($ft^3$): | | | |
|---|---|---|---|
| Containers | 22 LD-2 | or | 11 LD-3 |
| Forward | 40.78 (1440) | | 26.85 (948) |
| Aft | 33.98 (1200) | | 22.37 (790) |
| Bulk cargo (aft only) | 11.33 (400) | | 11.33 (400) |
| Total | 86.09 (3040) | | 60.55 (2138) |

Weights, kg (lb):

| | |
|---|---|
| TOGW | 122 470 kg (270 000 lb) |
| OEW | 78 300 kg (172 610 lb) |
| MLW | 112 570 kg (248 160 lb) |

Propulsion: Two CF6-6D2



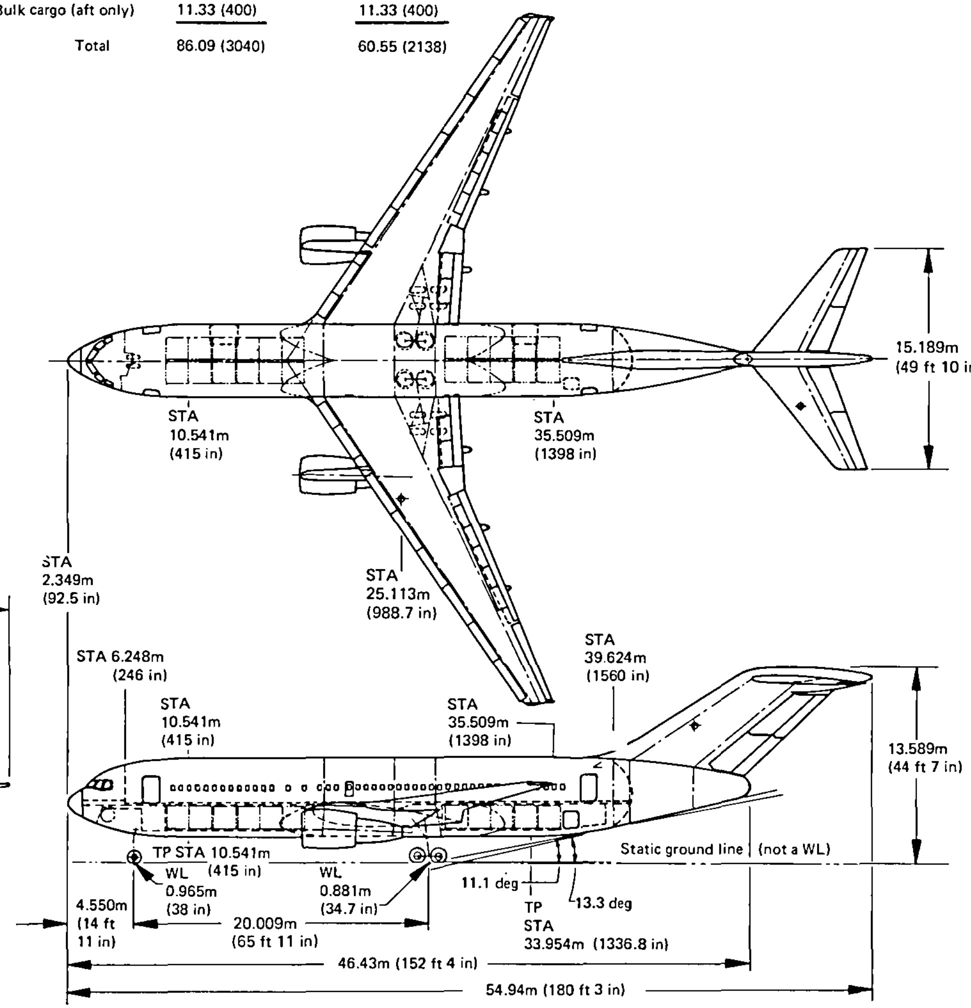




*Figure 7. Conventional Baseline Airplane Configuration (768-102)*

*Table 2. Conventional Baseline Airplane Characteristics (768-102)*

| | |
|---|---|
| Configuration | |
| • Passengers | 197 mixed class, 207 tourist |
| • Containers | 22 LD-2, or 11 LD-3 |
| • Engines | (2) CF6-6D2 |
| Design mission | |
| • Cruise Mach | 0.8 |
| • Range | 3590 km (1938 nmi) |
| • Takeoff field length | 2210m (7250 ft) |
| • Approach speed | 70 m/s (136 kn) |
| • Noise | FAR 36, Stage 3 |
| • Flying qualities | Current commercial transport practice |
| Airplane technology | Current commercial transport practice (aerodynamics, structural, propulsion, etc.) |

The existing data base was reviewed and additional analyses were conducted as necessary to complete the technical description and to calibrate the preliminary design tools to be used on the ACT airplane design.

### 5.1.2 DESIGN REQUIREMENTS AND OBJECTIVES

The overall strategy of the IAAC Project was to identify the benefits due to ACT functions by carefully including only changes due to active controls, while retaining other characteristics of the Conventional Baseline Airplane configuration. For instance, the ACT configurations were to be no quieter than the baseline, if improved noise characteristics would result in a performance/economic penalty. The foundation for achieving the project objectives consistently was identifying the design requirements and objectives (DRO) for the baseline, and then carefully developing an understanding of what had to be changed to allow the incorporation of active controls. The requirements had to be carefully crafted to allow any beneficial application of ACT without compromising airplane safety. This modified DRO became the basis for all of the ACT airplane designs.

The resulting ACT airplane DRO shows that most of the conventional airplane requirements apply with little or no modification, with the exception of the flying qualities criteria. For example, the ACT airplane does not have a specific unaugmented stability requirement. Therefore, the flying qualities design criteria normally used in the design of commercial transports do not apply. A conventional airplane will typically exhibit safe, if not satisfactory, flying quality characteristics following the failure or functional loss of any augmentation systems or automatic controls that are included in the design. In contrast, an ACT airplane designed to be dependent upon augmentation will experience degraded characteristics if that augmentation system should totally fail.

A set of flying qualities design criteria patterned after those of Reference 5 has been adopted for the purposes of this project. These criteria provide design guidance for both augmented and unaugmented airplane characteristics and are distinct from the criteria for certification of ACT airplanes. Since the federal airworthiness

regulations are a statement of minimum safety requirements and already address failure of critical systems, it appears that new certification regulations are not required.

The other significant area of departure from the Conventional Baseline Airplane DRO was the specification of flutter criteria. Current commercial jet transport flutter criteria require that the airplane shall be shown to be flutter free:

- o By analysis and model tests, up to a speed 20% beyond the design dive speed (i.e., 1.2 $V_D$).

- o By flight test, to the design dive speed (i.e., $V_D$).

The IAAC Project criteria for an airplane that incorporates a flutter-mode control system require that the airplane shall be shown to be flutter free:

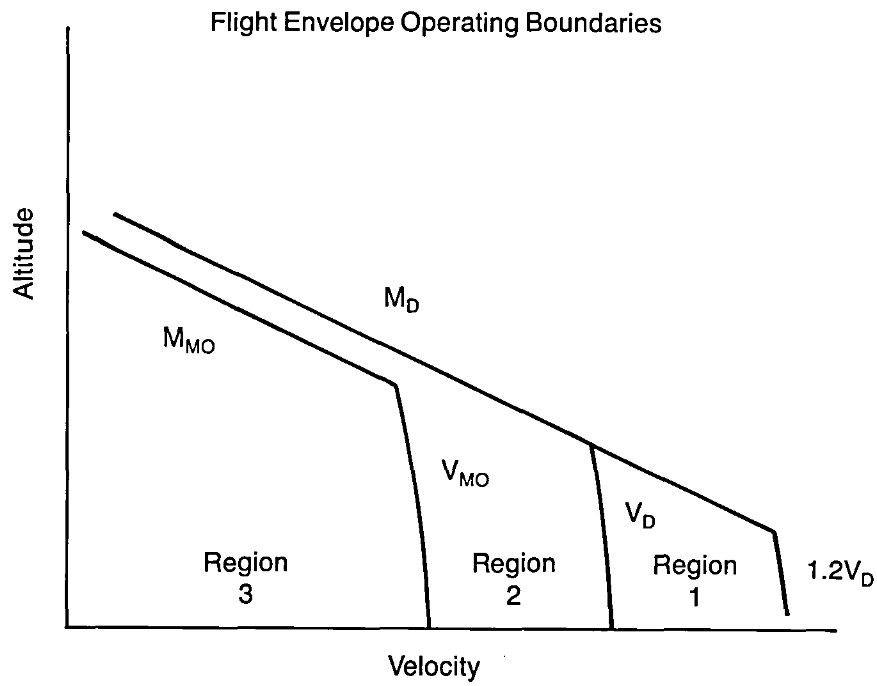
- o By flight test, with the flutter-mode control (FMC) inoperative, throughout the normal operating envelope up to the maximum operating speed (i.e., $V_{MO}/M_{MO}$).

- o By flight test, with the FMC operational, up to the design dive speed (i.e., $V_D$).

- o By analysis and model test, with the FMC inoperative, up to the design dive speed (i.e., $V_D$).

- o By analysis and model test, with the FMC operational, up to a speed 20% beyond the design dive speed (i.e., 1.2 $V_D$).

Figure 8 summarizes and compares these two flutter criteria. A more detailed discussion of the ACT aspects of the design requirements and objectives used in the IAAC Project is contained in Appendix A of Reference 6.




Criteria

Airplane shall be free from flutter in accordance with:

| Region | Current criteria for conventional airplanes | Criteria for airplanes with flutter mode control |
|---|---|---|
| 1 | By analysis and model test to $1.2V_D$ | By analysis and model test to $1.2V_D$ with FMC on |
| 2 | By flight test to $V_D$ | By analysis and model test to $V_D$ with FMC off<br><br>By flight test to $V_D$ with FMC on |
| 3 | By flight test to $V_{MO}$ | By flight test to $V_{MO}$ with FMC off |

*Figure 8. Flutter Criteria*

### 5.1.3 INITIAL ACT AIRPLANE

The airplane configuration tasks in the IAAC Project proceeded under the assumption that any active control function that would benefit the airplane could be implemented in a suitable system. A beneficial application in this context means that from both a performance and an economic point of view, the inclusion of the ACT function yields an improved airplane. In parallel with this airplane configuration work, another set of tasks examined the implementation of the ACT functions. This system work is summarized in Section 5.2.

The first ACT airplane designed under the IAAC Project is referred to as the Initial ACT Airplane, Model 768-103. The objectives of this first step were to identify the performance and economic benefits of ACT when applied with certain constraints, and to establish an approach to the integrated application of ACT to commercial transport design. The benefits were determined as compared to the Conventional Baseline Airplane. The integrated design approach led to new levels of communication between the various technical disciplines that make up the design team.

#### 5.1.3.1 Active Control Functions

Candidate active control functions were selected for the Initial ACT Airplane configuration based on a preliminary assessment of the expected benefit in airplane weight or drag reduction. No formal quantitative risk-vs-benefit evaluation was made prior to selecting the following functions:

- Pitch-Augmented Stability (PAS) - The PAS function augments the airplane's longitudinal stability to provide acceptable flying qualities. Both long-period (phugoid) and short-period (static stability) augmentation are included. No minimum acceptable unaugmented pitch stability is specified.

- Lateral/Directional-Augmented Stability (LAS) - The LAS function is provided by a conventional yaw-damper identical to that of the baseline airplane.

- o Angle-of-Attack Limiter (AAL) - The AAL function prevents the airplane from exceeding a specified angle of attack. The limiting angle of attack exceeds that required for maximum lift by a small margin.

- o Wing-Load Alleviation (WLA) - The WLA function has two submodes:
  - o Maneuver-Load Control (MLC) - The MLC function reduces the wing's vertical bending moment in longitudinal maneuvers by means of symmetric deflection of the outboard ailerons to redistribute the wing loads inboard.
  - o Gust-Load Alleviation (GLA) - The GLA function attenuates the wing loads due to atmospheric disturbances (turbulence and gusts) by means of appropriate deflection of the outboard ailerons to reduce and redistribute the induced loads.

- o Flutter-Mode Control (FMC) - The FMC function stabilizes the wing's critical flutter mode beyond $V_D/M_D$. This stabilization is accomplished by sensing wing normal acceleration and commanding appropriate deflection of a small wing-trailing-edge control surface.

- o Fatigue reduction and ride-improvement functions were not explicity included, but were to be considered in the design of the above functions.

The safety impact of failure of an ACT function flows directly from the degree of the airplane's dependence on that function for continued safe flight. Terminology was selected at the start of the Initial ACT Airplane design to describe these various levels of dependence and their associated reliability requirements. The various documents that have been published over the course of the IAAC Project have consistently reflected this nomenclature. The Federal Aviation Administration (FAA) has recently published an Advisory Circular that addresses this topic (ref. 7). Table 3 shows the current FAA terminology, its relationship to the terminology used throughout the IAAC Project documentation (and continued herein), and the associated reliability requirements.

*Table 3. ACT Criticality Levels and Associated Reliability Requirements*

| Probability of Function Loss (On the Order of) | Original IAAC Criticality Designation | FAA AC-25-1309 Criticality Designation | Test ACT System Element Designation |
|---|---|---|---|
| Extremely Improbable ($1 \times 10^{-9}$)* | Crucial | Critical | Essential |
| Improbable ($1 \times 10^{-5}$)* | Critical | Essential | Primary |

* Probability of loss of function in a flight of 1-hour duration.

### 5.1.3.2 Ground Rules

There were several ground rules for the design of the Inital ACT Airplane that need to be understood because of their influence on the particular benefits assessment for this airplane. First, the airplane takeoff gross weight, propulsion system, wing (planform and area, airfoil sections, and cruise shape), and empennage (planform and airfoil sections) characteristics were constrained to the same as the baseline.

The empennage areas were determined from the analysis of the configuration. The selected constraints allowed the use of aerodynamic, structural, propulsion, and weight data from the baseline. This in turn led to a credible, cost-effective performance and economic assessment.

Second, the airplane configuration design proceeded under the assumption that any ACT function that was determined to be beneficial to the airplane could be made available. In this context, "available" means that the function could be implemented with suitable reliability, availability, and economics.

Finally, certain important options present in the Conventional Baseline Airplane were retained in order to make the clearest possible assessment of the economic benefits of ACT. For example, space provisions were included for the upper-deck cargo door and the lower-deck pallet door. These space provisions, and room for their use by ground equipment if they were subsequently implemented, were considered in the reconfiguration work that led to the Initial ACT Airplane.

Throughout the Configuration/ACT-System Design and Evaluation Task of the IAAC Project, technology levels for the structure, propulsion system, and aerodynamics were held constant at the level established by the Conventional Baseline Airplane configuration. This was done so that any beneficial changes would be due solely to ACT.

### 5.1.3.3 Configuration

The general arrangement and principal dimensions of the airplane that resulted from this work are shown in Figure 9. The airplane beneficially incorporated all of the previously listed ACT functions.

The control system philosophy on this airplane was to incorporate ACT with minimum change to the baseline control system. This was accomplished by incorporating secondary servos that sum mechanically with the existing control system. The only exception to this was the introduction of a flutter mode control surface as the inboard end of the outboard aileron, which was electrically commanded. The implementation is reflected in the control system surface assignments shown in Figure 10.

The motivation for changing the configuration stemmed from the desire to balance the airplane with a further-aft cg. Accomplishing this would produce three beneficial effects:

1) The cruise L/D would be improved

2) The required empennage area would be reduced

3) The airplane empty weight would be reduced

Two modifications were made to the baseline airplane in order to accomplish this:

1) The wing was moved forward on the body

2) The main landing gear's effective center of rotation was moved aft relative to the wing

Geometry:

| | | | |
|---|---|---|---|
| Body cross section, m (in) | | | |
| Shape | Vertical double lobe | | |
| Maximum width | 5.029 (198.00) | | |
| Maximum height | 5.410 (213.00) | | |
| Landing gear | Nose | Main | |
| Type | Dual | Truck | |
| Location, m (in) | BS 6.896 (271.50) | 64.7% MAC | |
| Spacing, m (in) | 0.609 (24) | 1.143 x 1.422 (45 x 56) | |
| Tire size, m (in) | 0.939 x 0.330-0.406 (37 x 13-16) | 1.092 x 0.393-0.508 (43 x 15.5-20) | |
| Oleo stroke, m (in) | 0.381 (15) | 0.508 (20) | |
| Aerodynamic surfaces | Wing | Vertical tail | Horizontal tail |
| Area, $m^2$ ($ft^2$) | 256.3 (2759)[a] | 54.0 (581) | 32.0 (344) |
| Aspect ratio | 8.71[a] | 0.67 | 4.00 |
| Taper ratio | 0.267[a] | 0.700 | 0.400 |
| Sweep at c/4, deg | 31.5[a] | 55.0 | 35.0 |
| Incidence, SOB, deg | 3.8[a] | – | – |
| Dihedral, deg | 6.0[a] | – | -3.0 |
| Root t/c, percent | 15.1 | 12.0 | 11.0 |
| Tip t/c, percent | 10.3 | 12.0 | 9.0 |
| Root chord, m (in) | 8.567 (337.30)[a] | 10.558 (415.74) | 4.038 (158.98) |
| Tip chord, m (in) | 2.286 (90.0)[a] | 7.392 (291.01) | 1.615 (63.59) |
| MAC, m (in) | 6.031 (237.47)[a] | 9.070 (357.07) | 3.000 (118.10) |
| Span, m (in) | 47.244 (1860.0) | 6.014 (236.76) | 11.306 (445.13) |
| Tail arm, m (in) | – | 21.679 (853.50) | 28.633 (1127.28) |
| Tail volume coefficient[b] | | 0.090 | 0.551 |

Engine toe-in angle = 1 deg to a BBL
Nacelle incidence = 2.625 deg to a BWL
Wing upper surface at SOB rib at WL 4.940m (194.5 in)

[a]Trapezoid geometry quoted: aero reference area = 275.1 $m^2$ (2961 $ft^2$)

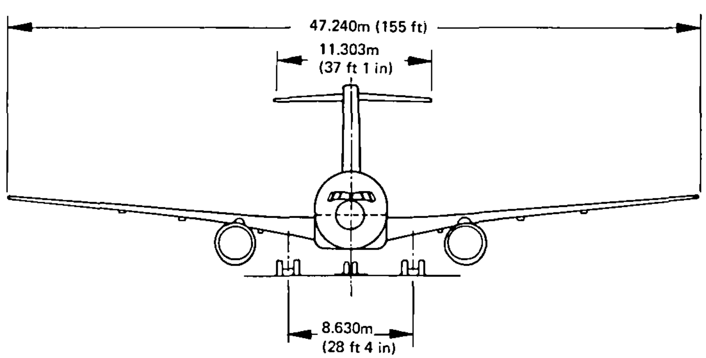
[b]Based on aero reference area

| Passenger accommodations: | Passengers | Abreast | Pitch |
|---|---|---|---|
| First class | 18 | 6 | 0.965m (38 in) |
| Tourist | 179 | 7 | 0.864m (34 in) |
| Cargo and baggage, $m^3$ ($ft^3$): | | | |
| Containers | 22 LD-2 | or | 11 LD-3 |
| Forward | 33.98 (1200) | | 22.37 (790) |
| Aft | 40.78 (1440) | | 26.85 (948) |
| Bulk cargo (aft only) | 11.33 (400) | | 11.33 (400) |
| Total | 86.09 (3040) | | 60.55 (2138) |

Weights, kg (lb):

| | |
|---|---|
| TOGW | 122 470 (270 000) |
| OEW | 77 370 (170 560) |
| MLW | 111 640 (246 110) |

Propulsion: Two CF6-6D2



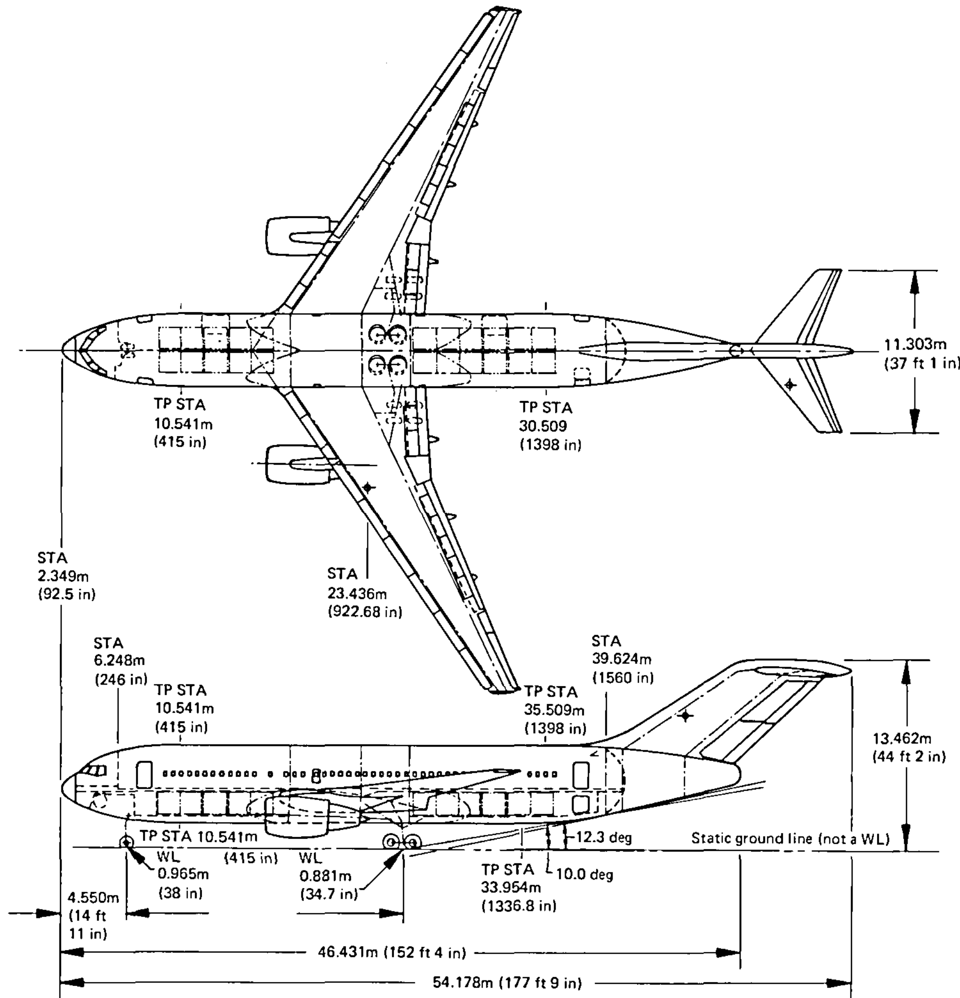
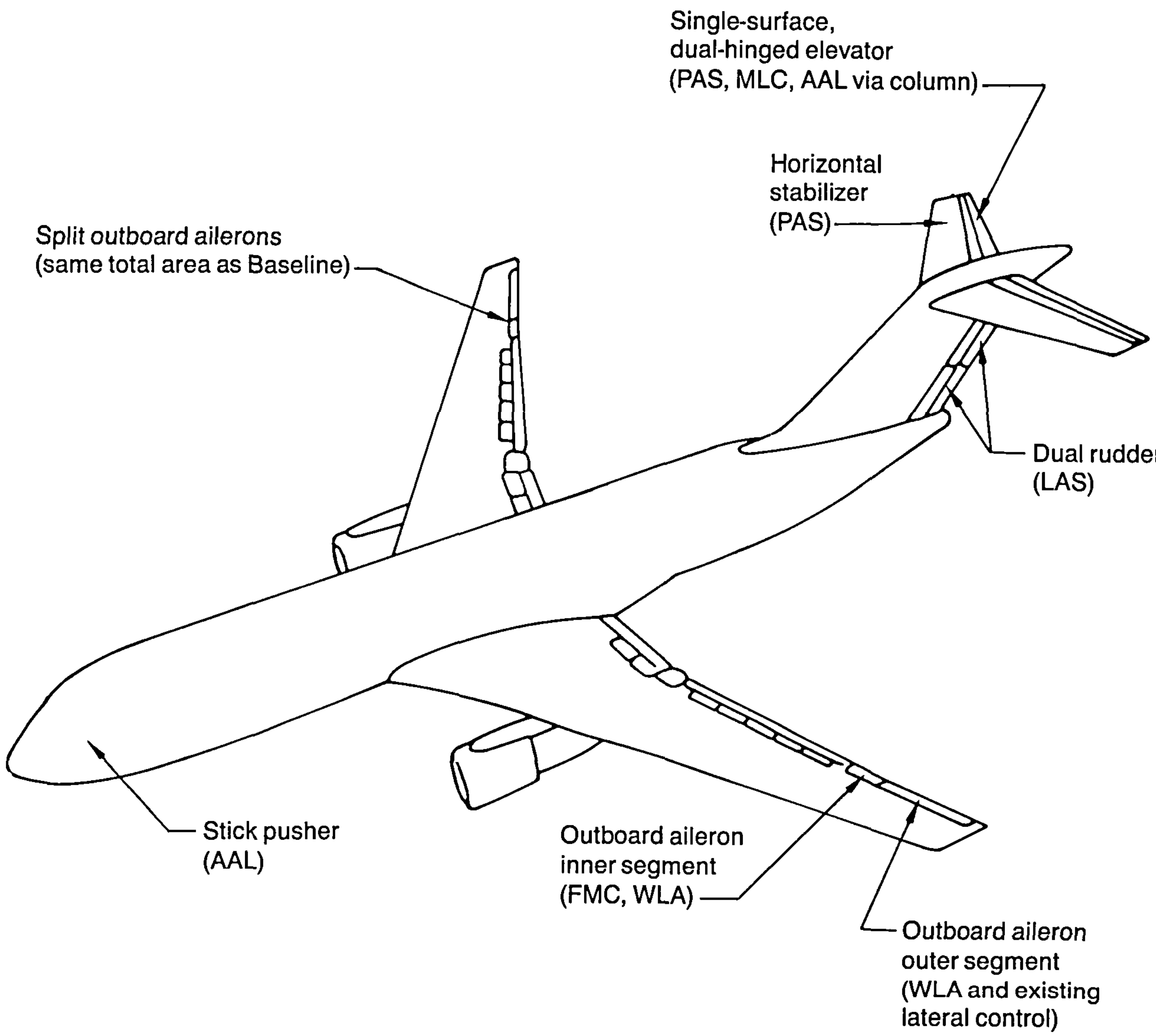




*Figure 9. Initial ACT Airplane Configuration General Arrangement*




| ACT function | Control |
|---|---|
| PAS (short period) | Elevator |
| PAS | Elevator and stabilizer |
| LAS | Rudder |
| AAL | Column, elevator |

| ACT function | | Control |
|---|---|---|
| WLA | MLC | Outboard aileron, elevator (through PAS command) |
| | GLA | Outboard aileron |
| FMC | | Outboard aileron (inner segment) |

*Figure 10. Initial ACT Airplane Control Surfaces*

The balance of the changes dealt with the change to the unaugmented stability requirement and the incorporation of ACT. Table 4 shows the comparison of the Conventional Baseline and the Initial ACT airplane configurations. The wing forward movement was made in approximately 66-in steps (the length of one cargo container) to preserve the lower deck cargo capacity of the baseline airplane. Since the ground rules called for the retention of the wing planform and main landing gear attachment to the wing rear spar, a change in landing gear concept was necessary to accomodate the aft shift of the cg.

#### 5.1.3.4 Performance and Economics

The Initial ACT Airplane exhibits lower drag than the baseline due to reductions in trim and skin-friction drag associated with the smaller empennage, further-aft cg, and longer tail arm resulting from the wing shift. The Initial ACT Configuration was not resized to the baseline mission (both airplanes have the same gross weight, engine size, wing area, and payload); consequently,the Initial ACT Airplane has a 13% increase in range at the same takeoff gross weight and payload as the Conventional Baseline Airplane. Adjusted to the 3590-km (1938-nmi) baseline mission range, this becomes an approximately 6% reduction in block fuel. Table 5 shows the Conventional Baseline/Initial ACT comparison, and Figure 11 shows the block fuel reductions and their sensitivity to range.

Return on investment (ROI) for the airplane operator is a more complete measure of the benefit associated with ACT than is airplane performance alone. Incremental ROI was selected as the appropriate metric for an ACT airplane. Since ACT is being examined as an alternative to conventional design, the incremental ROI is a measure that would support such a choice. The ROI estimation is based on a 300-airplane program, the $300,000/airplane incremental cost of incorporating ACT in the design, and fuel savings of 352 lb/flight hr (average operating range). This yields a 15.7% incremental return on investment; i.e., the incremental capital costs (based on factored cost data) for design, development, and installation of the equipment and configuration differences between the Initial ACT and Conventional Baseline configurations. This 15.7% ROI was based on the 1978 $0.1057/liter ($0.40/gal) fuel cost (1978 dollars). A much larger ROI would result from using current fuel prices.

*Table 4. Changes From Conventional Baseline to Initial ACT Configuration*

- Wing moved 66 in. forward on body
- Main landing gear effective center of rotation moved aft (relative to the wing) 8.9% $\bar{c}_W$
- Double-hinged elevator
- Horizontal tail area reduced 276 ft$^2$ (45%)
- Vertical tail area reduced 37 ft$^2$ (6%)
  (due only to wing movement)
- ACT functions assumed
  - Pitch augmented stability (PAS)
    - Pitch
    - Speed
  - Angle of attack limiting (AAL)
  - Wing load alleviation (WLA)
    - Maneuver load control (MLC)
    - Gust load alleviation (GLA)
  - Flutter mode control (FMC)
- cg range reduced 3% $\bar{c}_W$
- Typical cruise cg shifted aft 9.5% $\bar{c}_W$
  (relative to wing)

*Table 5. Conventional Baseline and Initial ACT Airplane Performance Comparison*

| | Baseline | | Initial ACT | | Δ | |
|---|---|---|---|---|---|---|
| MTW, kg (lb) | 122 920 | (271 000) | 122 920 | (271 000) | --- | |
| TOGW, kg (lb) | 122 470 | (270 000) | 122 470 | (270 000) | --- | |
| ZFW, kg (lb) | 104 400 | (230 160) | 103 470 | (228 110) | -930 | (-2050) |
| MLW, kg (lb) | 112 560 | (248 160) | 111 640 | (246 110) | -930 | (-2050) |
| OEW, kg (lb) | 78 300 | (172 610) | 77 370 | (170 560) | -930 | (-2050) |
| Forward cg, percent MAC | 10.0 | | 21.0 | | +11.0 | |
| Average cruise cg, percent MAC | | 20.5 | | 31.8 | | (+11.3) |
| Cruise L/D, (M = 0.8, $C_L$ = 0.45) | | Base | | (+3.6) | | (+3.6) |
| SAR, km (nmi) | 3 589 | (1 938) | 4 061 | (2 193) | +472 | (+255) |
| TOFL, SL, 29°C (84°F) m (ft) | 2 210 | (7 250) | 2 118 | (6 950) | - 92 | (-300) |
| $V_{APP}$ at maximum landing weight, m/s (kn) | 70.0 | (136.1) | 68.6 | (133.4) | -1.4 | (-2.7) |
| Landing field length, sea level, dry, at maximum landing weight, m (ft) | 1 443 | (4 735) | 1 402 | (4 600) | -41 | (-135) |

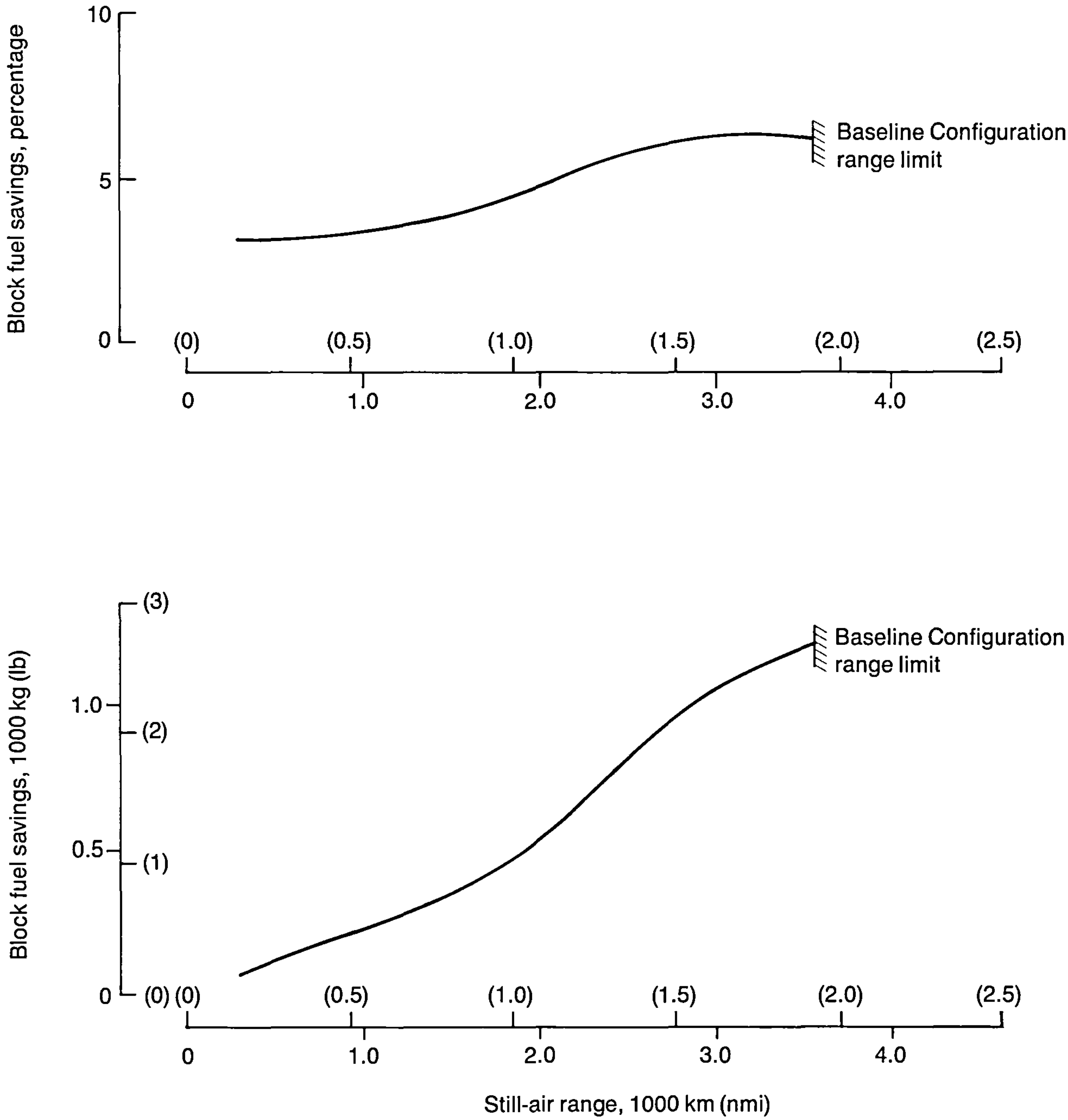



*Figure 11. Initial ACT Block Fuel Savings*

The performance and economic benefits estimated for this Initial ACT Airplane were very encouraging, especially in light of the rather constraining ground rules applied to the design. The largest benefit is due to the incorporation of PAS and AAL. It could be argued that one of the most significant benefits of ACT results from the additional freedom the airplane designer is given. The Initial ACT Airplane illustrated that point to a limited degree and shows significant performance improvement at a reasonable, predicted, incremental ROI. The details of the Initial ACT Airplane configuration study are reported in References 6 and 8. The required ACT control systems appeared feasible with the technology available at the time these studies were initiated. The system studies will be summarized in Section 5.2.

### 5.1.4 WING PLANFORM EFFECTS

The Wing Planform Study was the second configuration development step of the IAAC Project. The objectives of this work were to:

- o Determine the effect of changes in wing planform (aspect ratio and sweep) on the overall performance of an airplane incorporating ACT functions from the outset of the commercial transports design process. The wing thickness was varied as necessary to maintain constant cruise speed.

- o Through sensitivity analyses, identify any significant impact on study results of key assumptions made in the technical approach.

- o Select a Final ACT Airplane configuration from the Initial ACT Airplane data in combination with the results of the Wing Planform Study.

Figure 12 shows the IAAC ACT airplane configurations, and the relationship of the Wing Planform Study to the balance of the configuration studies. Details of this study are contained in References 9 and 10.

Before selecting the specific airplanes to be designed under this Wing Planform Study, a matrix of wing geometry candidates was selected. This matrix included wing sweep changes ($\pm 5$ deg) and increased aspect ratios up to 14 (based on trapezoidal wing area).

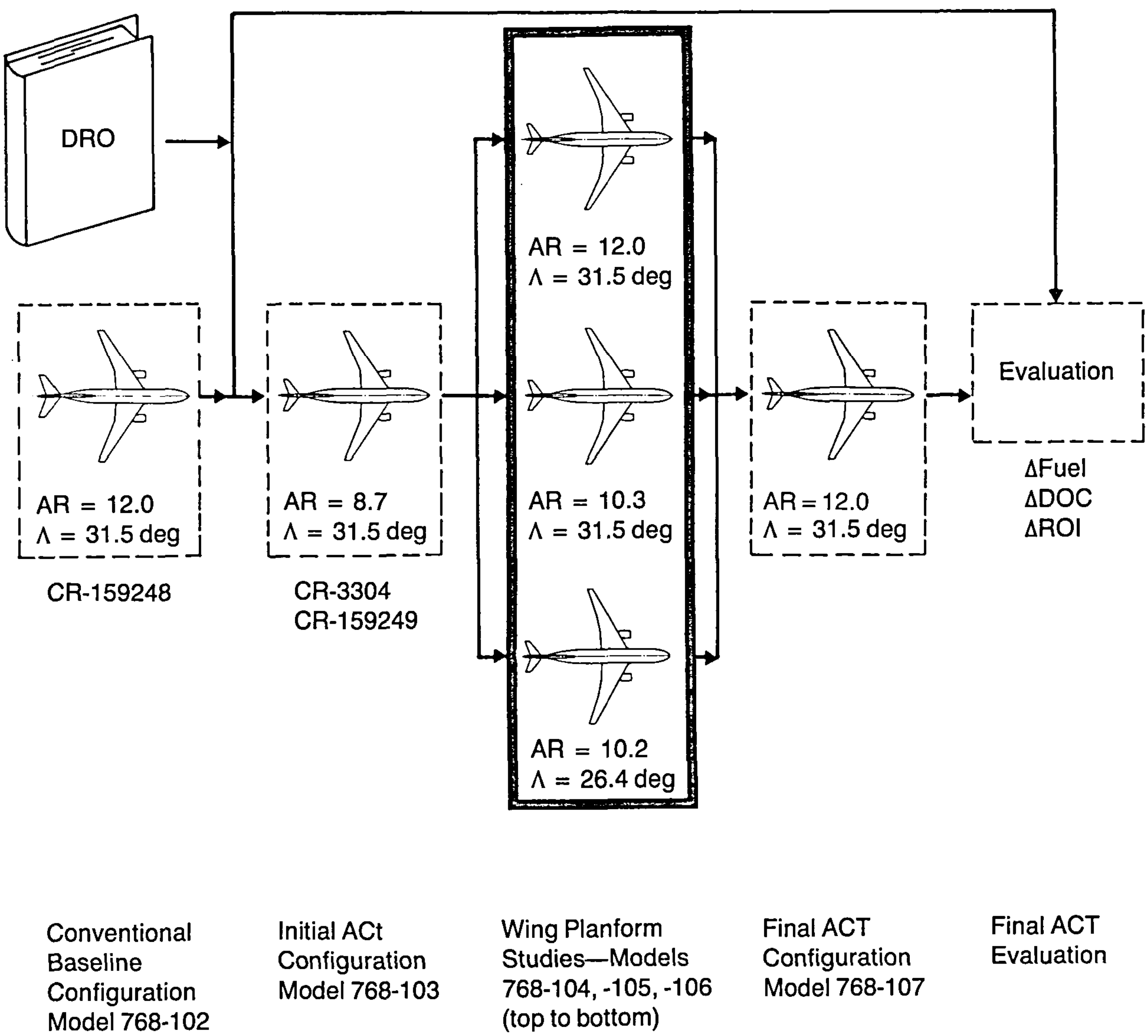



*Figure 12. IAAC Project ACT Airplane Configuration Evolution*

This matrix of wings is shown in Figure 13 with three of the more important trends that were factors in the study. The wings selected for the study are shown shaded in the last part of the figure.

As shown in Figure 13a, over this region of wing geometry L/D improves as sweep is reduced and as aspect ratio is increased. The trend of airplane operating empty weight reduction is almost directly opposite that of L/D, as illustrated in Figure 13b. This results from the reduction in wing weight, for airplanes of about the same wing area, as the span is reduced and/or the wing thickness is increased.

Airplane ground handling requirements limit the minimum distance between the furthest aft cg and the effective center of the main landing gear footprint. This problem is especially severe for twin-engine airplanes with the engines mounted under the wing. The problem stems from the high thrust-to-weight ratio typical of twin-engine transports, and the low thrust line associated with wing-mounted engines. A wing-mounted main landing gear was required in order to provide the same operational flexibility as the baseline; i.e., a sufficiently low footprint pressure to allow operation at airports such as LaGuardia in New York. When these considerations are combined with the desire to locate the cg well aft on the wing, the problem is compounded. Finally, with increasing wing sweep and aspect ratio, the size of the inboard trailing-edge extension necessary to contain the wing-mounted main landing gear becomes excessively large. The direction of the "increasing gear complexity" arrow in Figure 13c reflects these design difficulties.

Figure 13d shows the three planforms that were selected for the Wing Planform Study and their relationship to the Conventional Baseline and Initial ACT Airplane wing planforms.

Airplane configurations were developed with the three selected wing geometries. These airplanes were designed to have the same takeoff gross weight and propulsion system as the Conventional Baseline and Initial ACT airplanes. The wing areas were sized for about the same approach speed. Fuselage shape and size, and passenger and lower lobe container arrangements are identical to the Initial ACT Airplane. Assuming the same cg range due to payload and fuel shift, the wings were located on

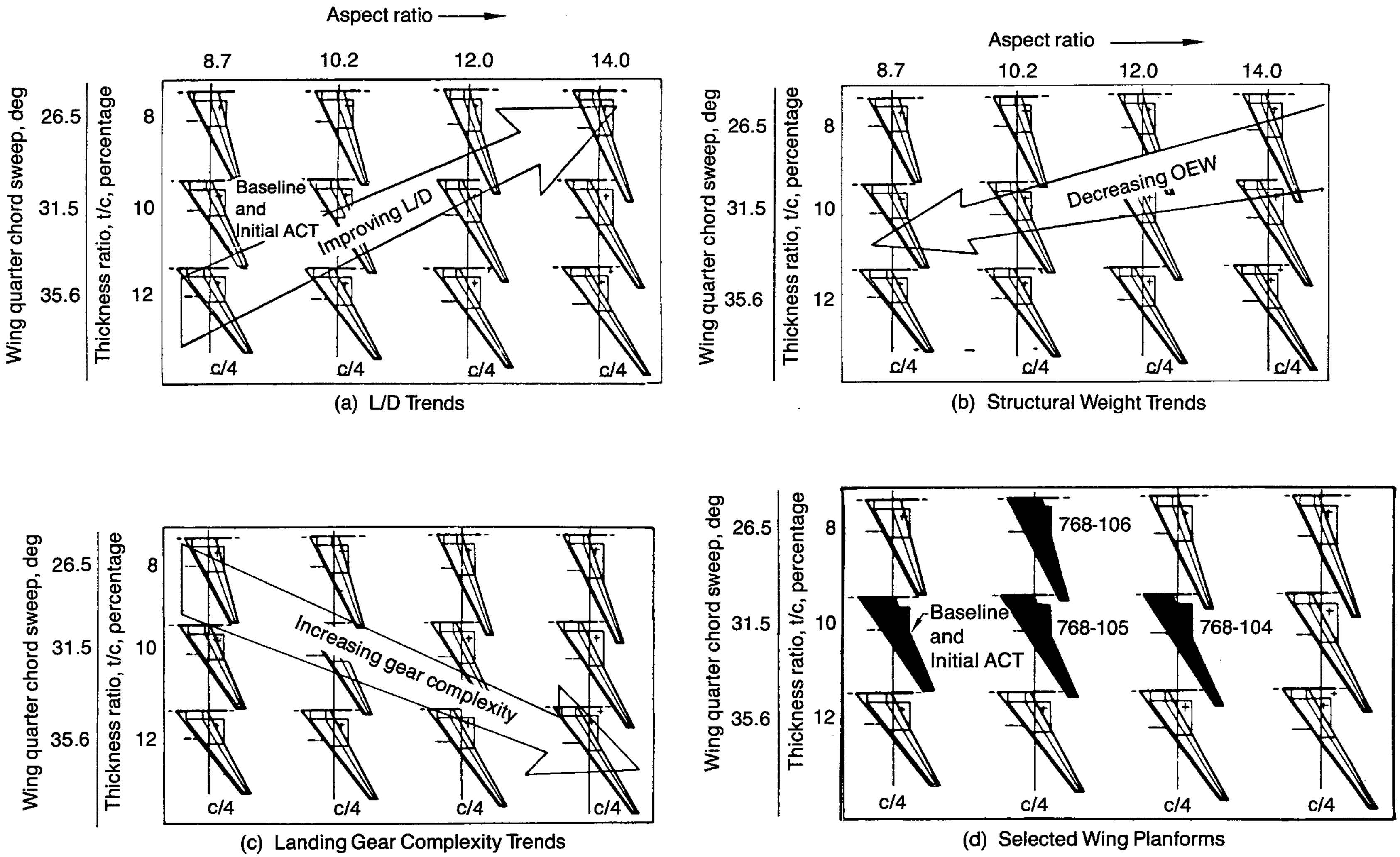



*Figure 13. Matrix of Candidate Wing Planforms*

the fuselage with the cruise cg position at 35% mean aerodynamic chord (MAC). The three wing planforms are shown overlaid with the Initial ACT Airplane wing in Figure 14. Note that the resulting wing planforms are very similar inboard of the engine, with minor variations in chord outboard. Horizontal and vertical tail geometries were maintained with sizes adjusted according to stability and control requirements. The landing gear configuration is the same as the Initial ACT Airplane, except for a cantilever support instead of a landing gear beam support on the aspect ratio 10.2, 26.5-deg sweep wing configuration.

The relative cruise efficiencies of the Conventional Baseline, the Initial ACT, and the three Wing Planform Study airplanes are shown in Figure 15. Cruise L/D for each of the ACT configurations improved approximately 1% due to the approximately 10% aft shift of the cruise cg, and improved about 2.5% due to the 45% reduction in horizontal stabilizer size. Both of these changes were made possible by the incorporation of pitch-augmented stability and angle-of-attack limiting. The nature of this cruise drag improvement for the Initial ACT Airplane is illustrated in Figure 15a. The cruise L/D data for these same configurations are shown as a function of wingspan in Figure 15b. The highest aspect ratio configuration (aspect ratio 12) shows approximately 10% improvement in L/D over the Conventional Baseline, due principally to three effects: lower trim drag, reduced tail size, and increased wingspan.

Relative block fuel is one important parameter in the performance assessment of the ACT configurations, i.e. the fuel required by the ACT configuration to accomplish the mission of the Conventional Baseline Airplane. The increased wingspan of the higher aspect ratio wings resulted in higher L/D and higher wing weights. Figure 16 shows the way these effects translate into relative block fuel/passenger mile and block fuel savings (relative to the Conventional Baseline). The best of these configurations, as judged by relative fuel use, exhibited block fuel savings of 10% at the design range. That aspect ratio 12 wing planform was selected for the Final ACT Airplane and will be discussed further in the next section.

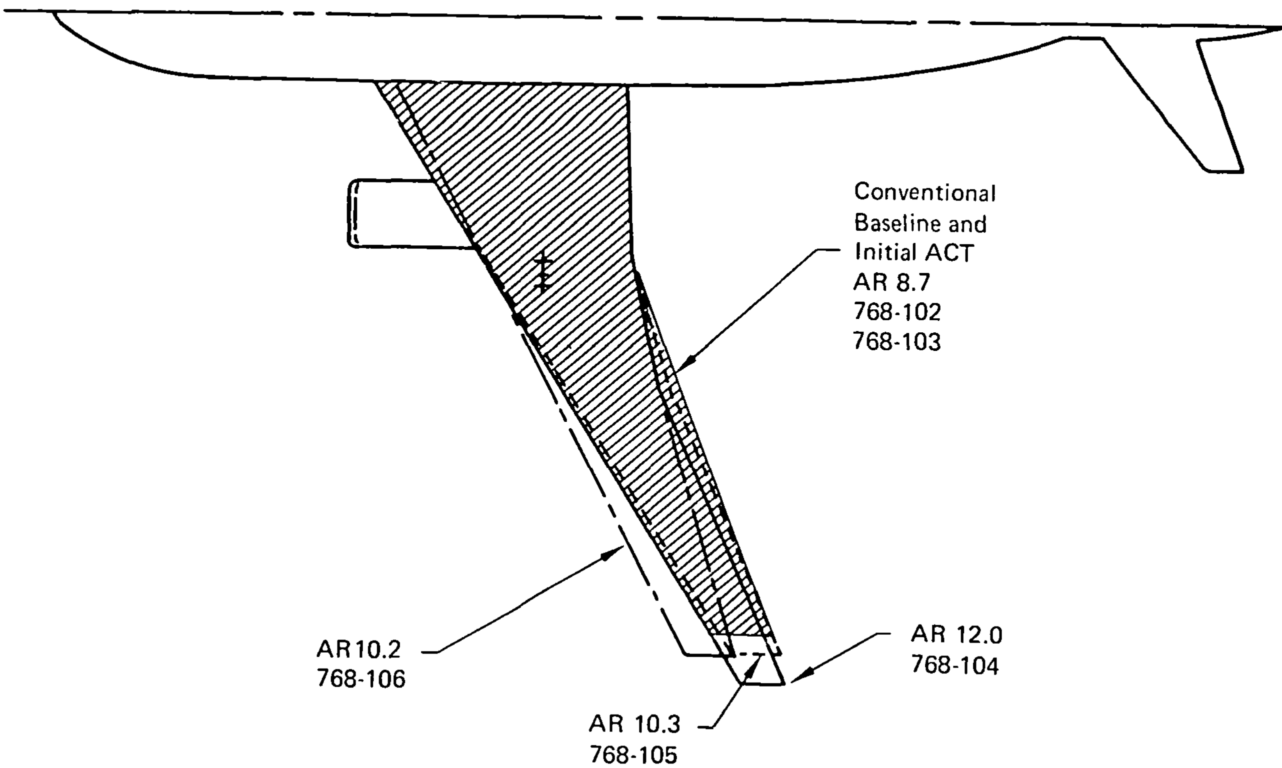



*Figure 14. Wing Planform Comparison*

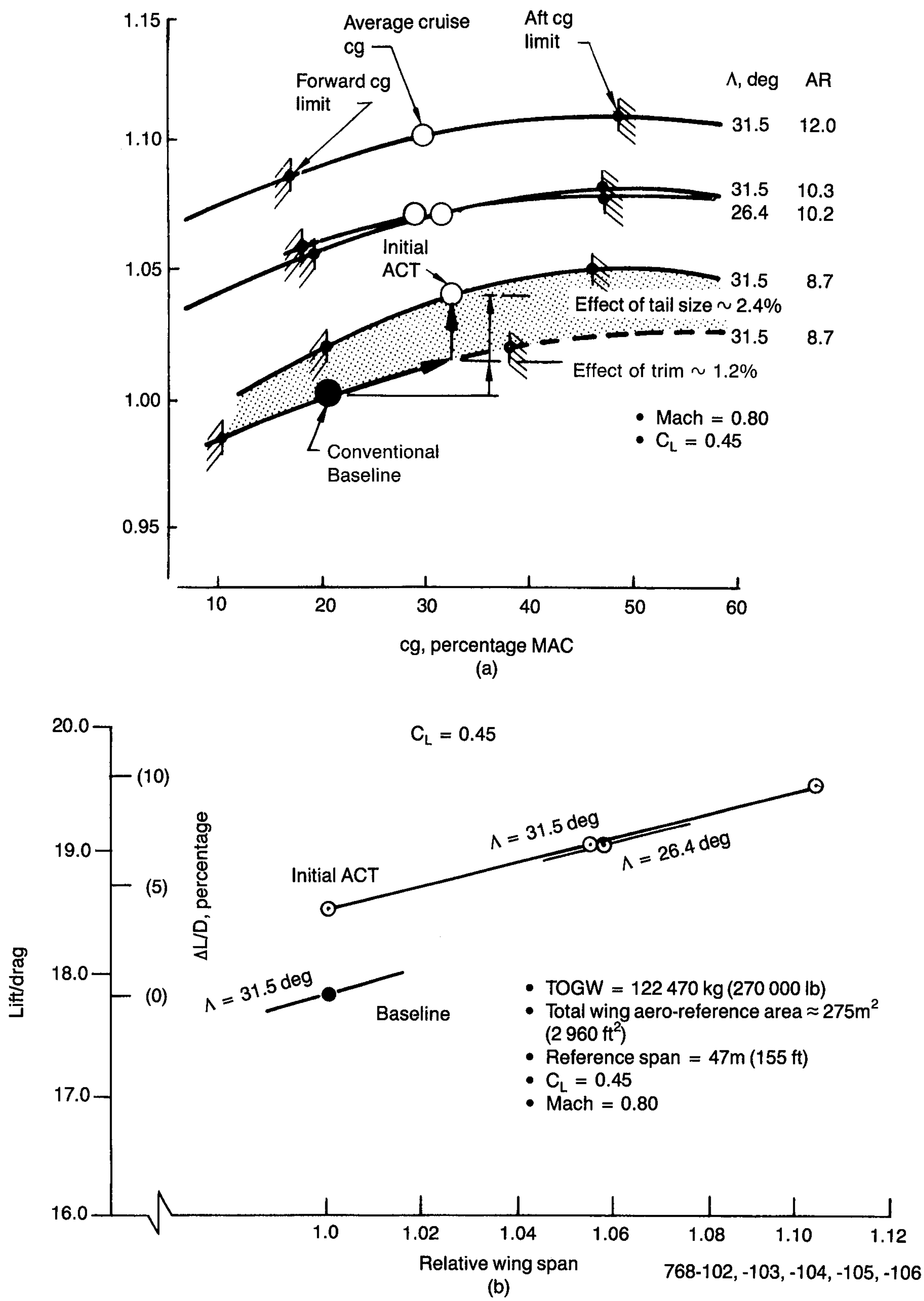



*Figure 15. Relative Cruise Efficiency*

- Takeoff gross weight = 122 470 kg (270,000 lb)
- 197 passengers
- SLST = 18 484 kg (40 750 lb)
- Total wing aero-reference area ~ 275 $m^2$ (2960 $ft^2$)
- Reference span = 47m (155 ft)

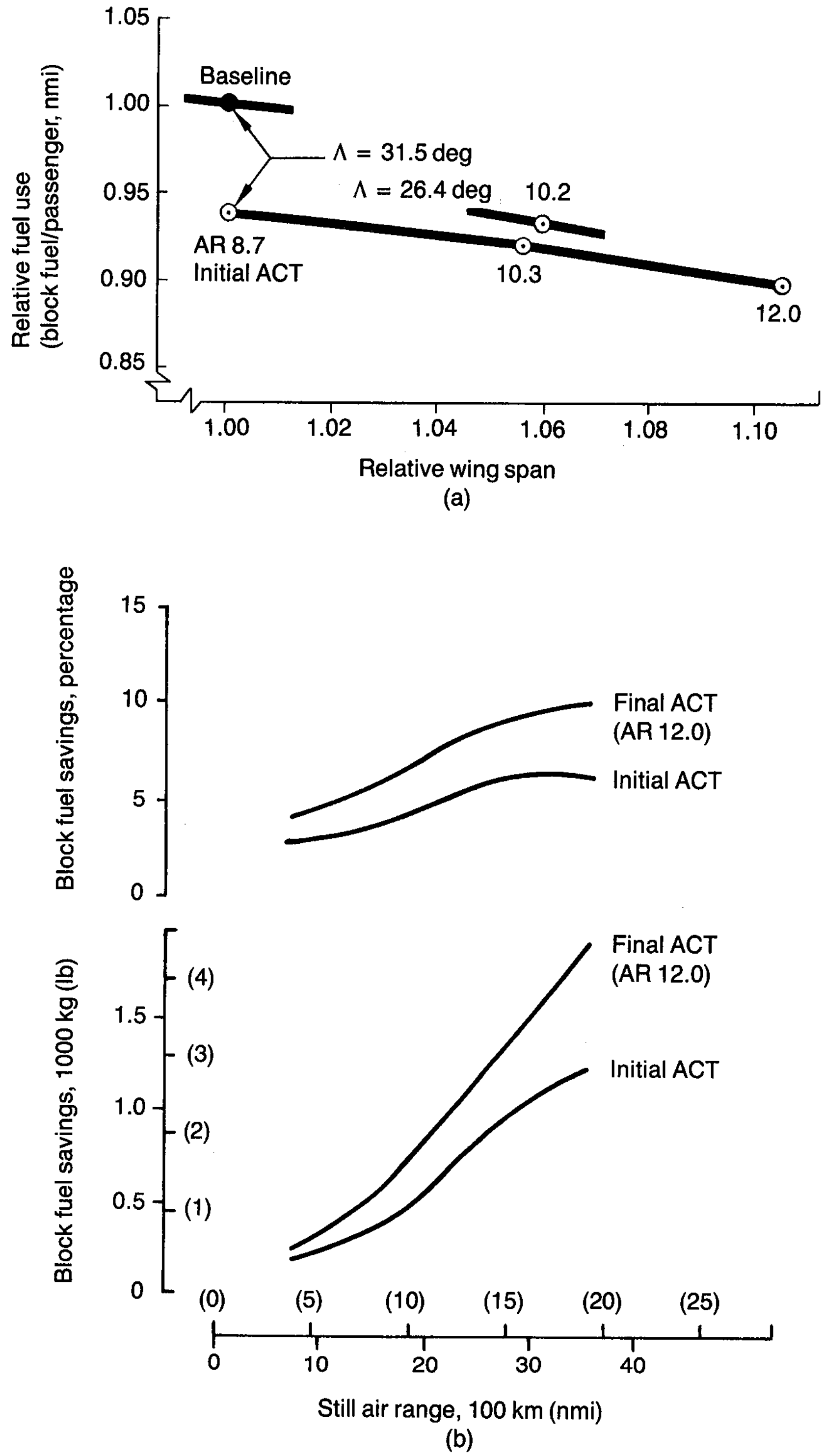



*Figure 16. Block Fuel Savings*

## 5.1.5 FINAL ACT AIRPLANE

The Final ACT Airplane configuration (Model 768-107) is shown in Figure 17. It is geometrically identical to the aspect ratio 12 Wing Planform Study configuration (Model 768-104). The Final ACT Airplane was resized (gross weight reduction) to the baseline mission. Details of the selection of the Final ACT Airplane configuration are contained in References 9 and 10. Reference 11 contains the evaluation of the Final ACT Airplane.

The large wing-root chords required for landing gear integration with the further aft cg locations of the Final ACT Airplane resulted in a structurally efficient inboard wing box, which allowed the wingspan to be increased for only a modest weight penalty for flutter and dynamic gust conditions. Although flutter-mode control (FMC) and discrete gust-load alleviation (GLA) systems were synthesized, the surface rates required were judged too high for practical implementation, and neither system was included on the Final ACT Airplane. Rather, sufficient structural material was added to the wing to meet the gust loads and to passively provide the necessary flutter clearance. The ACT control system architecture for the Final ACT Airplane is shown in Figure 18. Deletion of FMC and GLA resulted in important simplification of the Initial ACT Airplane system architecture.

Final ACT Airplane performance improvements, with respect to the Conventional Baseline, are shown in Figure 19, along with a comparison of the two configurations (head-on and in planview). The increased wingspan of the Final ACT Airplane, compared to the Conventional Baseline, exhibited a 2% increase in empty weight and a slight increase in wing area, but yielded a 9.8% increase in cruise L/D. Takeoff field performance improved 15%, due principally to better climb performance resulting from trim drag reduction and lower drag due to lift from the larger span.

Off-design mission performance can also be an important factor in marketing a commercial transport. For example, airlines operating out of Denver may prefer an airplane with the full payload-range capability available for the high-altitude, hot-dry conditions often encountered during the summer. The active controls and greater span of the Final ACT Airplane make this possible, yielding 51% greater range out of Denver (hot day) than the Conventional Baseline Airplane.

Geometry:

| | | | |
|---|---|---|---|
| Body cross section, m (in) | | | |
| Shape | Vertical double lobe | | |
| Maximum width m (in) | 5.029 (198.0) | | |
| Maximum height, m (in) | 5.410 (213.0) | | |
| Landing gear | Nose | Main | |
| Type | Dual | Truck | |
| Location, m (in) | BS 6.896 (271.50) | 72.4% MAC | |
| Spacing, m (in) | 0.610 (24) | 1.143 x 1.422 (45 x 56) | |
| Tire size, m (in) | 0.940 x 0.330-0.406 (37 x 13-16) | 1.092 x 0.394-0.508 (43 x 15.5-20) | |
| Oleo stroke, m (in) | 0.381 (15) | 0.508 (20) | |
| Aerodynamic surfaces | Wing | Vertical tail | Horizontal tail |
| Area, m$^2$ (ft$^2$) | 226.8 (2441)[a] | 56.6 (609) | 32.0 (344) |
| Aspect ratio | 12.03[a] | 0.67 | 4.00 |
| Taper ratio | 0.267[a] | 0.700 | 0.400 |
| Sweep at c/4, deg | 31.5[a] | 55.0 | 35.0 |
| Incidence, SOB, deg | 3.8[a] | – | – |
| Dihedral, deg | 6.0[a] | – | -3.0 |
| Root t/c, percent | 15.1 | 12.0 | 11.0 |
| Tip t/c, percent | 10.3 | 12.0 | 9.0 |
| Root chord, m (in) | 6.855 (269.89)[a] | 10.811 (425.64) | 4.038 (158.98) |
| Tip chord, m (in) | 1.830 (72.06) | 7.568 (297.94) | 1.615 (63.59) |
| MAC m(in) | 4.827 (190.05)[a] | 9.285 (365.57) | 3.000 (118.10) |
| Span, m (in) | 52.222 (2056) | 6.157 (242.40) | 11.291 (444.53) |
| Tail arm, m (in) | – | 21.534 (847.78) | 28.709 (1130.27) |
| Tail volume coefficient[b] | – | 0.085 | 0.689 |

Engine toe-in angle = 1 deg to a BBL

Nacelle incidence = 2.625 deg to a BWL

Wing upper surface at SOB rib at BWL 4.953m (195 in)

[a]Trapezoid geometry quoted: aero reference area = 275.8 m$^2$ (2969 ft$^2$)

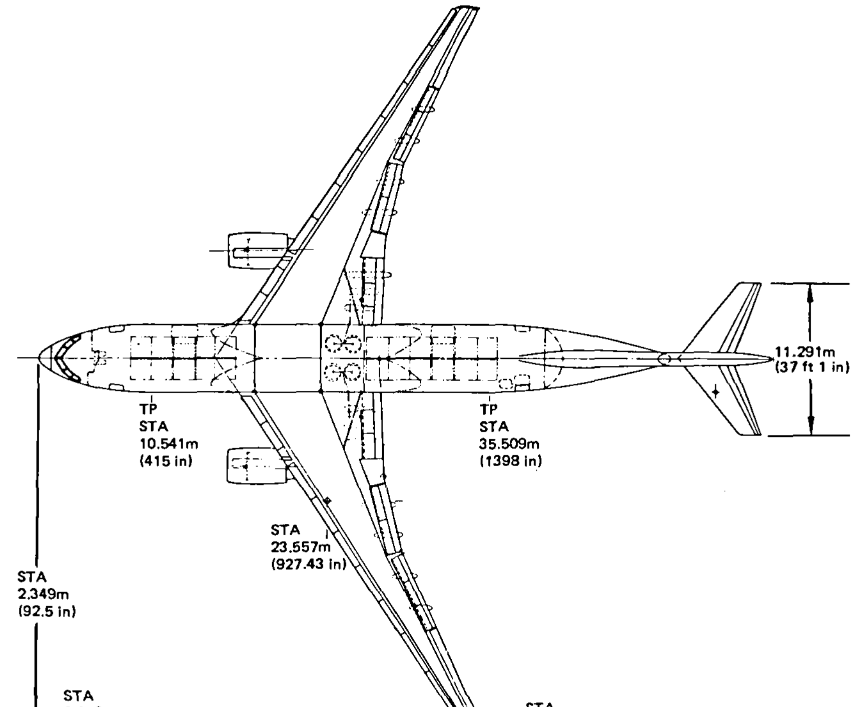
[b]Based on aero reference area

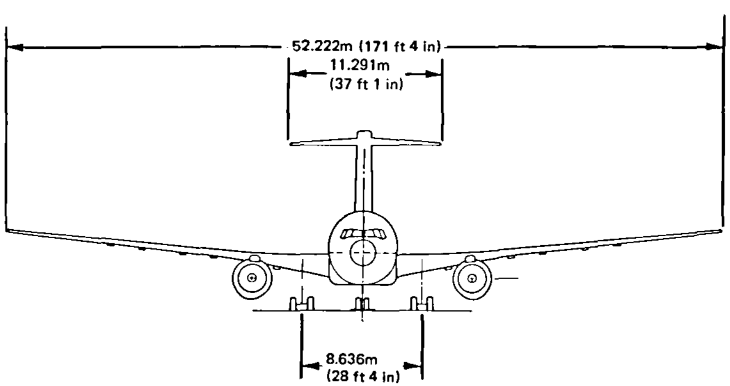
| Passenger accommodations: | Passengers | Abreast | Pitch |
|---|---|---|---|
| First class | 18 | 6 | 0.965m (38 in) |
| Tourist | 179 | 7 | 0.864m (34 in) |

| Cargo and baggage, m$^3$ (ft$^3$): | | | |
|---|---|---|---|
| Containers | 22 LD-2 or | 11 LD-3 or | 11 LD-4 |
| Forward | 33.98 (1200) | 22.37 (790) | 27.61 ( 975) |
| Aft | 40.78 (1440) | 26.85 (948) | 33.13 (1170) |
| Bulk cargo (aft only) | 11.33 ( 400) | 11.33 (400) | 11.33 ( 400) |
| Total | 86.09 (3040) | 60.55 (2138) | 72.07 (2545) |

| Weights, kg (lb): | |
|---|---|
| TOGW | 121 580 (268 040) |
| OEW | 79 890 (176 120) |
| MLW | 114 160 (251 670) |

Propulsion: Two CF6-6D2



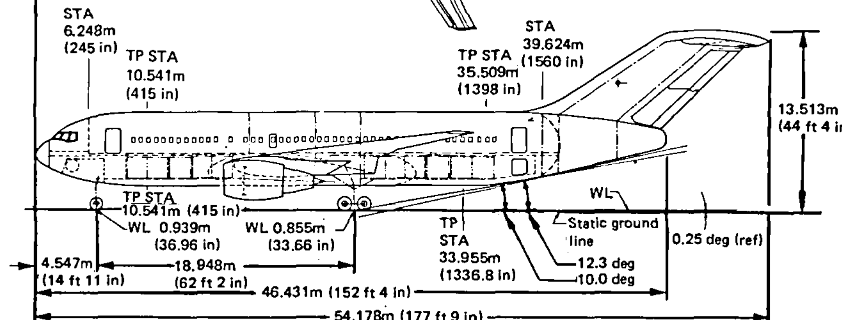




*Figure 17. Final ACT Airplane Configuration*

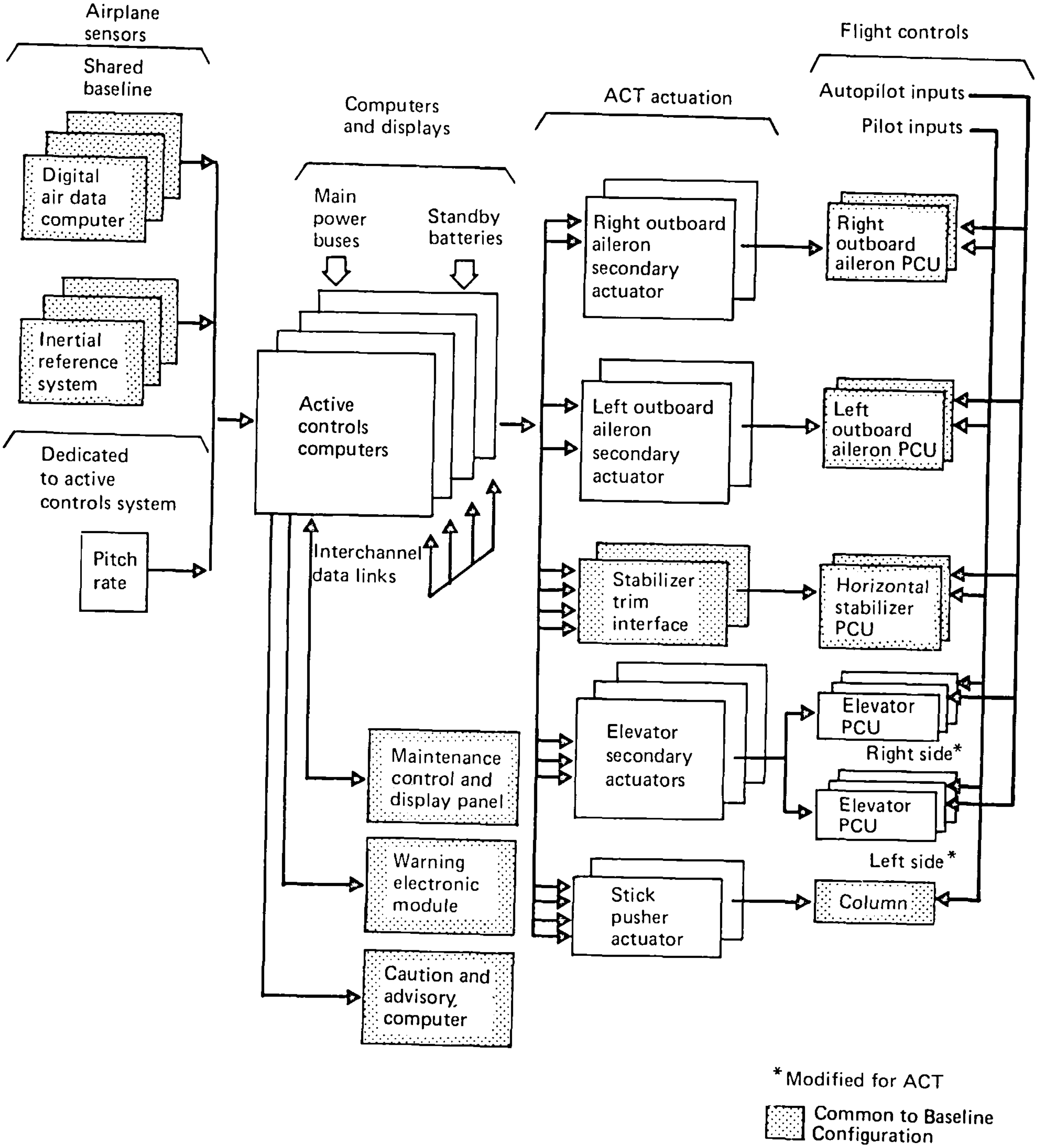



*Figure 18. Final ACT System Architecture*

- SAR = 3590 km (1938 nmi)
- 197 passengers
- Cruise Mach = 0.80

| | Baseline | | Final ACT | | Δ, percent |
|---|---|---|---|---|---|
| MTW, kg (lb) | 122 920 | (271 000) | 122 035 | (269 040) | -0.7 |
| TOGW, kg (lb) | 122 470 | (270 000) | 121 580 | (268 040) | -0.7 |
| OEW, kg (lb) | 78 295 | (172 610) | 79 885 | (176 120) | 2.0 |
| Wing area, $m^2$ ($ft^2$) | 275 | (2 961) | 276 | (2 969) | 0.3 |
| Engine size, kg (lb) | 18 485 | (40 750) | 18 485 | (40 750) | 0 |
| L/D ($C_L$ = 0.45, M = 0.80) | 17.82 | | 19.57 | | 9.8 |
| TOFL [SL 29°C (84°F)], m (ft) | 2 210 | (7 250) | 1 890 | (6 200) | -15.0 |
| $V_{APP}$, m/s (kn) (maximum LW) | 70 | 136.1) | 69 | (134.2) | -1.4 |
| Block fuel, kg (lb) | 19 925 | 43 930) | 17 920 | (39 500) | -10 |
| Denver performance | | | | | |
| SAR [1 625m (5 334 ft), 33.33°C (92°F)], km (nmi) | 2 370 | (1 280) | 3 590 | (1 938) | 51 |

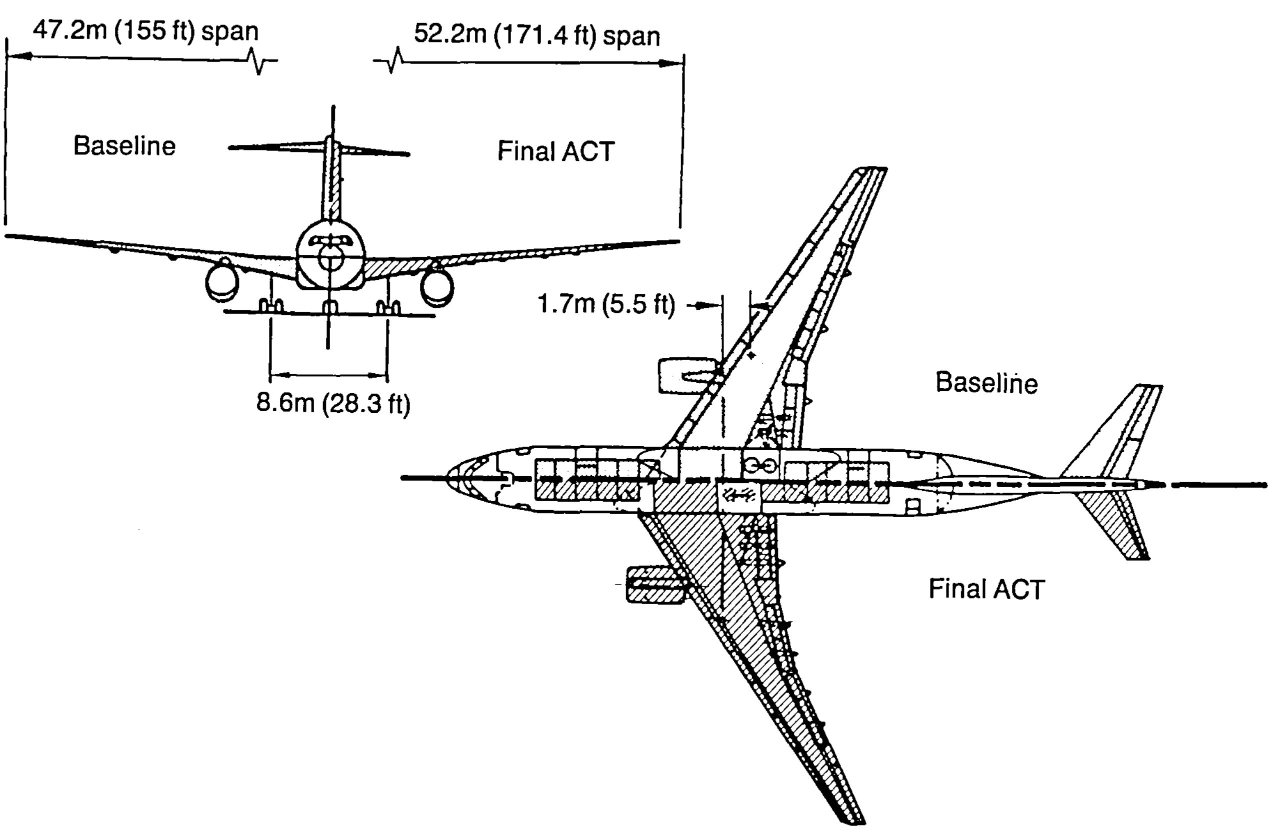



*Figure 19. Final ACT and Conventional Baseline Airplane Comparison*

The specific performance benefits of ACT are very configuration sensitive, but for the types of airplanes examined under the IAAC Project, several observations merit special mention. As shown in Figure 20, PAS and AAL functions are the most important sources of block fuel reduction. The percentage of fuel efficiency improvement due to these functions is by far the largest single effect noted for the airplanes studied. Clearly, the priority development or application of ACT should include these functions.

The Initial ACT Airplane exhibited 6.5% better fuel efficiency (at the design range of the Conventional Baseline) with the same wingspan as the baseline. The Final ACT Airplane showed a 10% improvement in fuel efficiency that was due, at least in part, to the increased wingspan. There is the question of whether the higher span configuration is viable without PAS and AAL, which could lead to accounting for the span-dependent increase in fuel efficiency as an ACT benefit.

ACT - either by itself or in concert with increased wingspan - can be used to produce a significant reduction in block fuel/passenger mi. The use of ACT without any change in wingspan should not impact ground operation. However, increased wingspan may impact ground operation of the airplane at airports where ramp and gate access is affected by wingspan. For example, at Chicago's O'Hare Airport, 7% fewer gates would be available to the Final ACT Airplane than were available to the Conventional Baseline or the Initial ACT Airplane. The fuel efficiency benefit of increased span would be weighed against a reduction in gate availability, with the outcome of such deliberations significantly influenced by fuel availability and price.

Reliability analyses showed that the ACT functions could be mechanized without significant adverse effect on dispatch reliability. The system also met the hardware reliability requirement for extremely remote probability of failures that results in loss of function; i.e., less than $1 \times 10^{-9}$ per 1-hr flight for the crucial pitch stabilization function. However, the prediction methodology available does not account for the probability of software error or other possible generic fault causes.

The Final ACT Airplane achieves a fuel savings of 10% at its design range when compared to the Conventional Baseline Airplane. An economic evaluation of the Final ACT configuration was performed using standard Boeing 1980 domestic cost methods (ref. 11). At a fuel cost of $0.26/l ($1.00/gal), the airplane yields an incremental rate

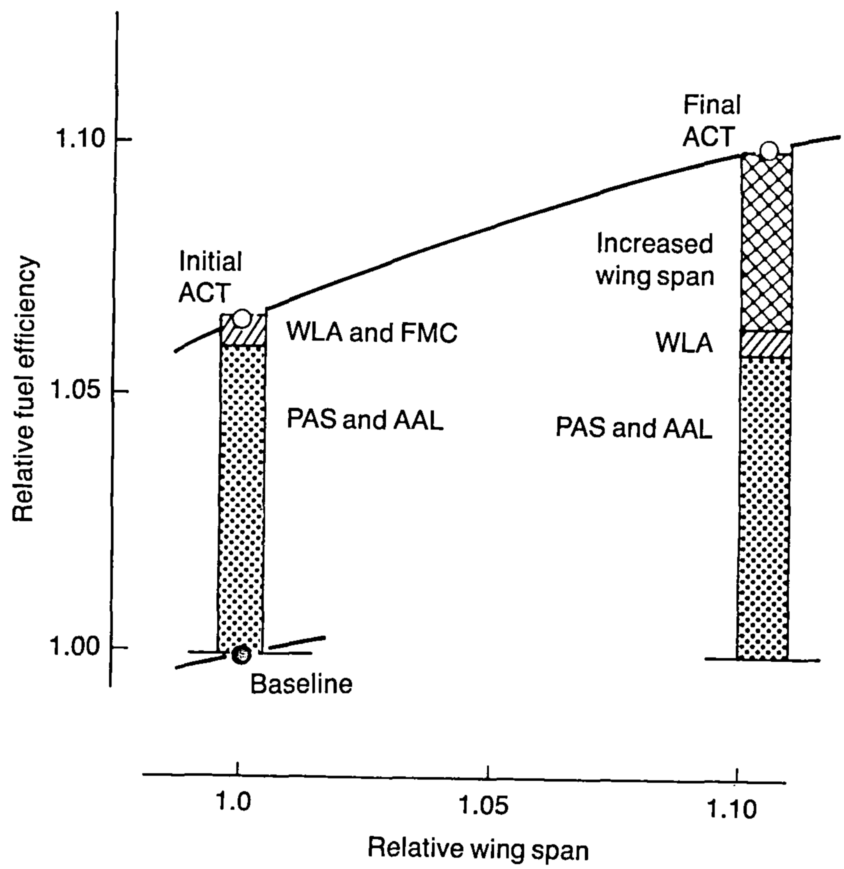



*Figure 20. Initial ACT and Final ACT Airplane Fuel Efficiency Comparison*

of return of 25% relative to the additional investment over the Conventional Baseline. Further, analysis shows that the ACT functions required for these performance and economic improvements can be provided with satisfactory dispatch and flight reliability. In achieving this performance, the technical risks are chiefly in system implementation. Although the systems described in these studies had multiple-redundant hardware, they typically had common software in all channels. Evidence gathered since indicates that systems whose failure probability must be extremely remote (i.e., less than $1 \times 10^{-9}$/1-hr flight) require both hardware and software dissimilar redundancy.

The airplane performance benefits identified by the IAAC Project are the result of a degree of dependence on control system function that is well beyond that of any currently certified commercial airplane. Commitment to commercial application will require additional development and testing, both laboratory and flight, to remove technical risks identified in this study. These risks are principally in the areas of system tolerance of faults and a cost-effective ACT system that provides the necessary availability and reliability.

## 5.2 ACTIVE CONTROLS TECHNOLOGY SYSTEMS

The IAAC Project ACT Airplane design work, described in Section 5.1, proceeded under the assumption that any beneficial ACT function could be implemented to provide satisfactory dispatch reliability for a cost of ownership acceptable to the airline, using technology currently available. The performance and economic assessments of the various ACT Airplane configurations were accomplished with these assumptions. The particular system definition needed only to be sufficiently detailed to allow an estimate of the development and production costs, the system weight (this is a relatively small part of the benefit assessment), and the system availability and reliability. These assumptions/approaches supported the various ACT Airplane performance and economic assessment tasks, but did not resolve the issues surrounding the questions of ACT system implementation. Therefore, two system analysis and development tasks proceeded in parallel with the airplane design work. These two tasks are discussed in the next two subsections (5.2.1 and 5.2.2).

### 5.2.1 CURRENT TECHNOLOGY ACT SYSTEM IMPLEMENTATION

The relationship of the Current Technology ACT Control System Definition Task to the IAAC Project is shown in Figure 3. The objectives of this work were to:

1) Define a highly reliable, low-technical-risk ACT control system for the IAAC airplane configurations using technology that was ready for commercial application when the task was initiated.

2) Support assessment of the benefit associated with the ACT Airplane by evaluating reliability, cost, and weight of the current technology system.

3) Identify technical risk areas and recommend any necessary system development and testing.

This system architecture work addressed implementation of all potentially beneficial ACT functions, not just those employed on a particular airplane configuration. The approach was to define and evaluate two extreme system architecture forms, then define a "selected system" that incorporated the best features of the extreme forms. The selected system was to meet the reliability requirement of crucial function failure probability of less than $1 \times 10^{-9}$ during a 1-hr flight with current technology system components. One very significant concern was latent errors in the software. There was no generally accepted method to prove the software to be error free. However, a disciplined approach was assumed effective in producing reliable real-time control software. The details of this work are contained in References 12 and 13.

#### 5.2.1.1 Task Overview

One very important element of the IAAC Project was the determination that the necessary ACT functions could be implemented in a low-technical-risk system. This was an important adjunct of the assessment of overall ACT benefits. It led to selection of a ground rule for the Current Technology ACT System work. Only system elements or components that were available and ready for commercial application at the outset of this task would be considered for implementation of the ACT system. It was recognized that this might lead to the use of somewhat heavier systems or,

potentially, to somewhat higher cost of ownership. However, it was judged more important to produce a low-risk system that did not depend upon any inventions than to press for an optimum system without consideration of the development risk.

The initial task of this current technology system definition work was to postulate a preliminary ACT control system. This preliminary system was used to assess ACT Airplane performance and economic benefits. This system was certainly not optimum, but the effect of this system choice on airplane weight and costs was judged to be acceptably small and would allow the performance and economic assessments to proceed in parallel with a more deliberate system definition.

During this subtask, it was determined that a predominantly digital system would best provide the many-faceted functions and associated redundancy management required. A key element of this decision was the recognition that system self-test could be much more readily implemented in a digital architecture than in an analog architecture. To find the best system architecture, with the highest reliability and lowest cost of ownership, two systems with extremely different architectures (one integrated and one segregated) were defined and analyzed. The Integrated System (fig. 21) accomplished all functions in a single set of digital computers, with the total computer redundancy level dictated by the most demanding ACT function. The counterpoint to the Integrated System is the Segregated System (fig. 22). Segregated does not mean the same as distributed, which addresses physical location of the system elements. Segregated means that each function is assigned to a specific set of digital computers, which would typically be smaller and less complex than those used in the Integrated System (fig. 21). The design and analysis of these alternative forms led to the Selected System, which combined the best features of both the Integrated and Segregated Systems.

### 5.2.1.2 ACT System Configuration

The keystone of the Integrated System is the set of four ACT computers that performs all functions and system self-tests and provides redundancy management. The relationship of those computers to other system elements is shown in Figure 21. Consistent with the low-technical-risk theme of this work is the manner in which the ACT system meshes with the balance of the airplane control system. The

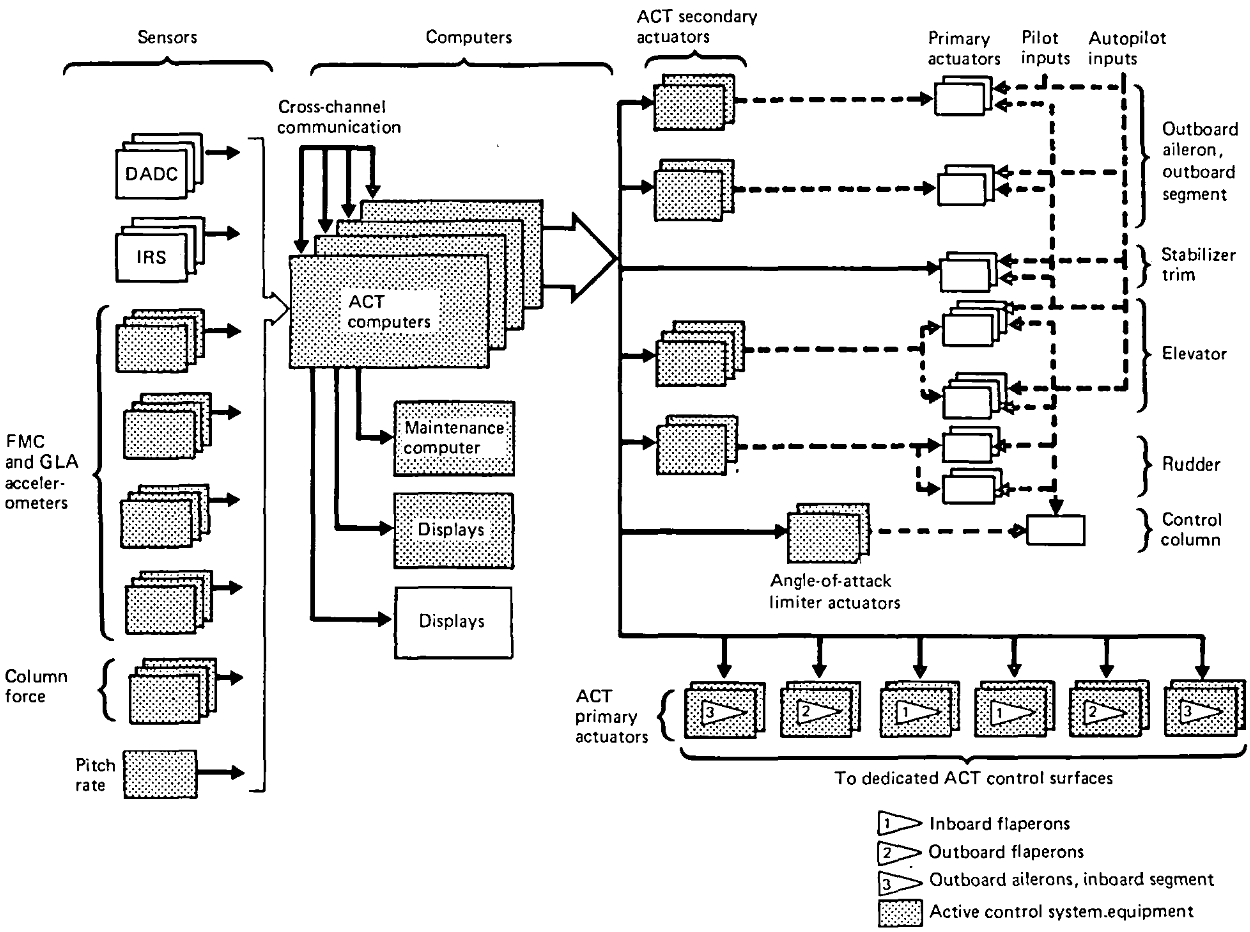



*Figure 21. Integrated System Configuration*

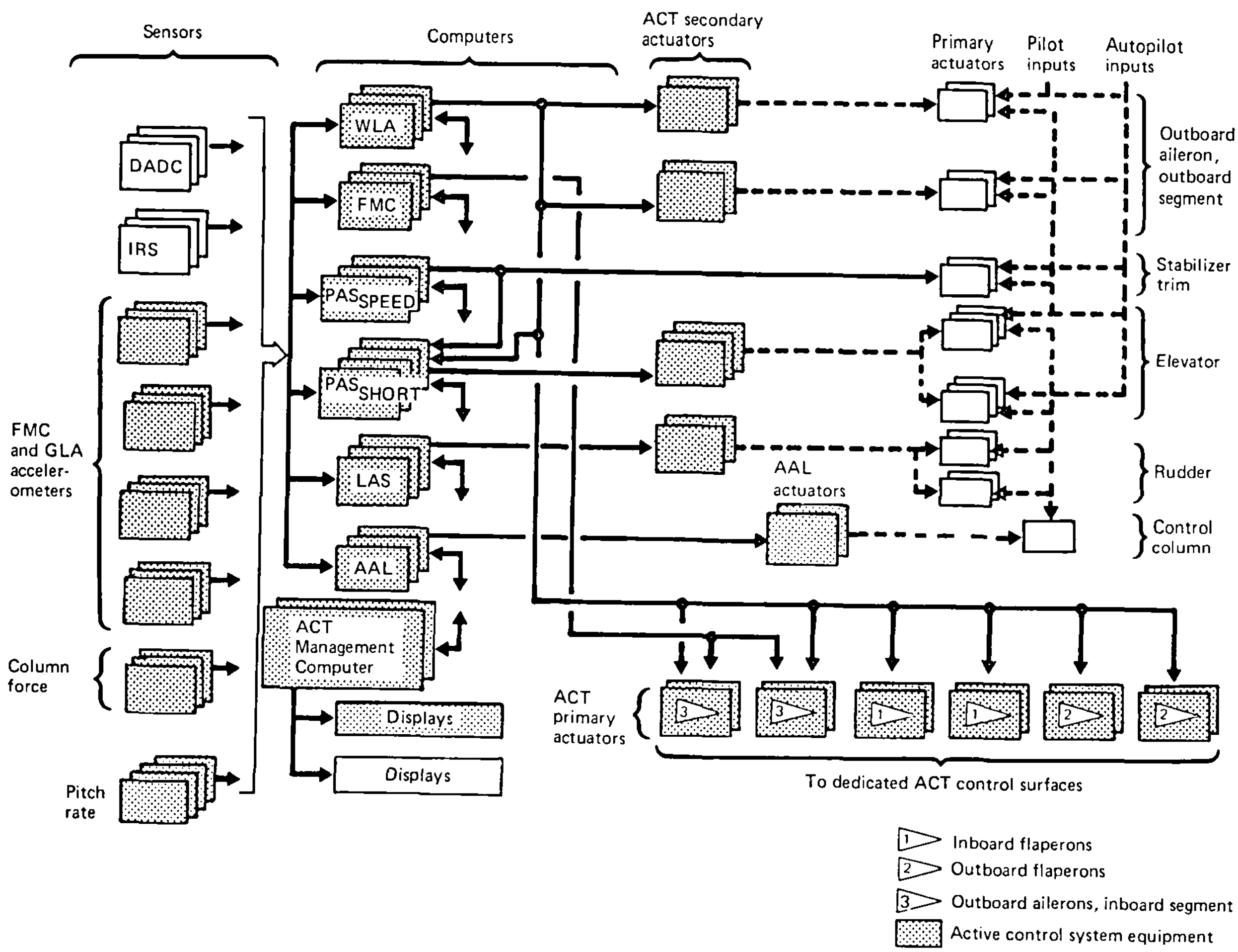



*Figure 22. Segregated System Configuration*

Conventional Baseline Airplane has a triplex digital air data computer (DADC) and a triplex inertial reference system (IRS). These systems became major sensors for the ACT system, but were not sufficient to provide all of the information necessary for the many ACT functions. For example, the crucial short-period PAS function required four pitch-rate signals. A single pitch-rate sensor was added to the system, complementing the triplex IRS, to provide the fourth signal.

The mechanical control system of the Conventional Baseline Airplane was retained by using secondary servos to add the voted ACT commands into the mechanical control path as shown in the right half of Figure 21. At the time system design work was underway, this was selected as the least controversial way to combine these signals, and provided a final, force-voted voting plane. The new ACT control surfaces (inboard flaperons, outboard flaperons, and the inboard segment of the outboard aileron) are electrically commanded and hydraulically actuated.

The principal difference between the Integrated and the Segregated systems is the substitution of 21 separate computers for the four ACT primary computers and the one maintenance computer of the Integrated System. These 21 computers, arranged as shown in Figure 22, perform each separate ACT function and provide redundancy management of the total system.

The only change to the sensors was the addition of three pitch-rate sensors, for a total of four, dedicated to the short-period PAS. This removal of the inertial reference system as an ACT system component was intended to increase the crucial function reliability. The output side of the system has the same architecture as the Integrated System.

One expectation of the Segregated System was improved reliability compared to the Integrated System. It was recognized that the issue would be whether the increase in the number of system components would result in a prohibitive cost of ownership for the Segregated System. The two systems used the same assumed digital computer component reliability. The probability of flight restrictions resulting from ACT system degradation did not improve as expected, but the probability of flight diversion and dispatch delay did improve. The Segregated System was almost 50% more expensive than the Integrated System. Careful consideration of these developments

highlighted the heavy dependence of ACT functions on the output of the DADC and pointed to an increased parts count in most of the digital computers as the reason for the overall decline in functional reliability. A careful examination of the attributes of these two system approaches led to the choice of the selected system.

The Selected ACT System is shown in Figure 23. The form of the Selected System results from the decision to perform the critical ACT functions and the full PAS function in a triplex set of primary computers. The full PAS function provides Cooper-Harper Level 1 (good) handling qualities, but the triplex set cannot provide sufficient reliability to accomplish the crucial short-period PAS functions; therefore, it is backed up by a quadruple set of essential computers. All communication to the elevator servos occurs through the Essential PAS computers. If a failure or failures result in loss of the ACT Primary computers, they are taken out of the control loop and the Essential PAS computers provide a minimum (Level 3) handling-qualities pitch augmentation using the four dedicated pitch-rate sensors. The minimum handling qualities are judged sufficient to safely land the airplane, but may not be sufficient to continue the mission as originally planned. Details of the implementation of each of the ACT functions and system redundancy management are contained in Reference 12.

### 5.2.1.3 Observations

The three control systems (Integrated, Segregated, and Selected) all met the reliability requirements. The Segregated System was predicted to be the most reliable, followed in order by the Selected and Integrated systems. The Integrated System appears to satisfy functional and reliability requirements at the lowest cost. The Segregated System failed to show the expected major improvements in reliability and exhibited unacceptably higher costs. The Selected System shows a decided reliability improvement over the Integrated System, with only a small increase in cost.

The major concerns that arise from review of these results are system complexity and the ever-present question of system reliability in the operational environment. Hardware reliability predictions are based on consistently conservative choices of appropriate values for the system elements, and in the techniques and system representations used in the reliability calculations. Although the absolute values of

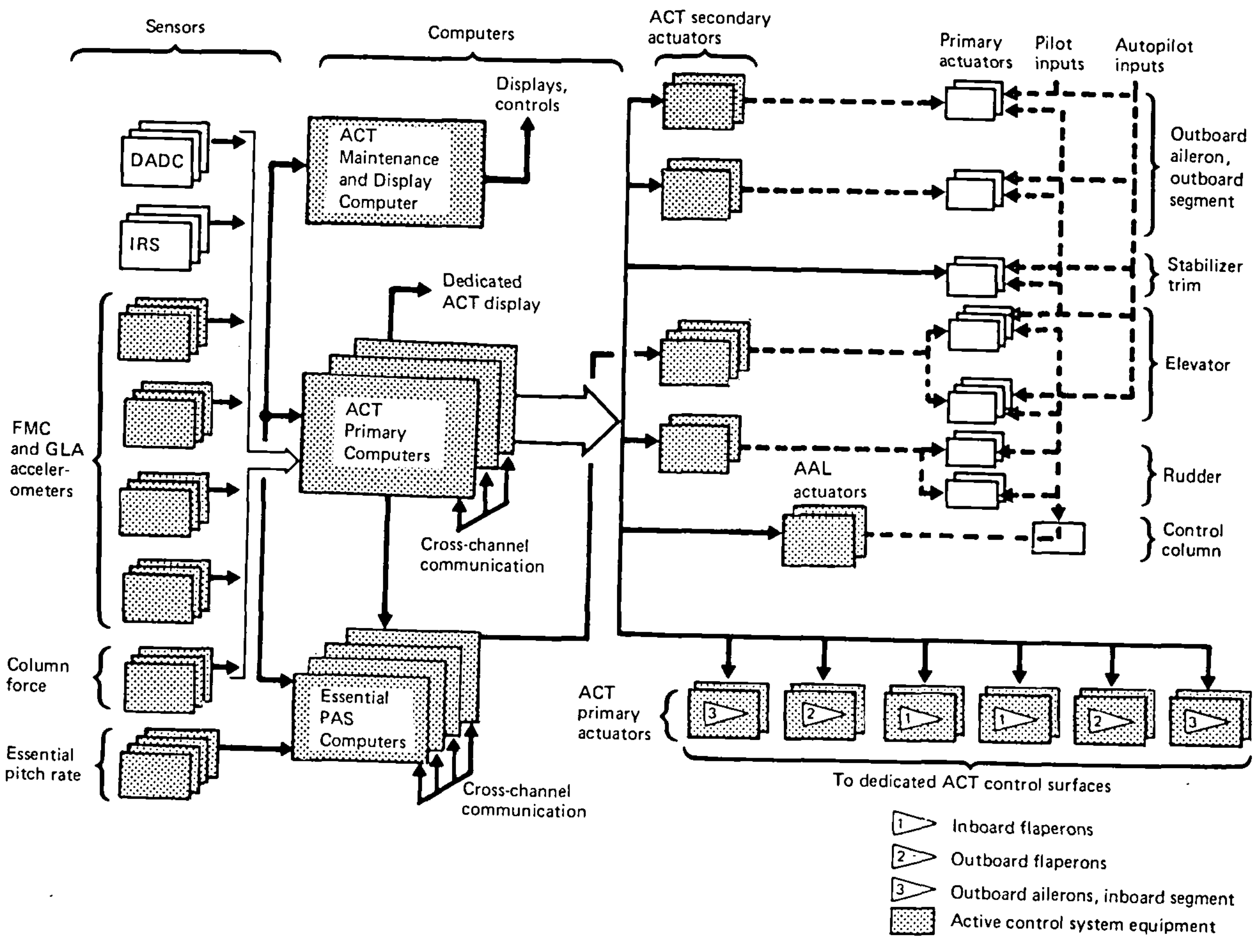



*Figure 23. Selected System Configuration*

the resulting reliability predictions may be suspect, their use as one of several figures of merit is considered well-founded.

There is no generally accepted method to prove software reliability equal to the required level. However, extensive experience in engineering real-time digital control systems for airplanes and spacecraft has shown that a process that begins with careful functional analysis and continues through requirements definition, design, coding, verification, validation, exhaustive testing, configuration control, and careful documentation can produce highly reliable real-time control software. Thus, it is concluded that the Selected System can be implemented using currently available technology and software design processes, although the ultimate production and certification of these systems will require significant additional experimental and confidence-building technical work.

### 5.2.2 ADVANCED TECHNOLOGY ACT SYSTEM IMPLEMENTATION

The overall objective of the Advanced Technology ACT Control System Definition Task was to define advanced ACT control systems for future commercial transports. The relationship of this task to the IAAC Project is shown in Figure 4. The task consisted of two subtasks: Advanced Technology ACT Control System - consisting of two elements, Advanced System Trade Studies and Implementation Alternatives - and ACT/Control/Guidance System. The specific objectives of this work were to:

- o Synthesize the ACT control laws directly, using optimal control theory.
- o Evaluate the effects of actuation system nonlinearities on gust-load alleviation and flutter-mode control.
- o Determine a 1990 advanced technology ACT control system architecture.
- o Define the expected air traffic environment of the 1990s and the effects of operating an ACT airplane in that environment.

- o Define an integrated ACT/Control/Guidance avionics and flight deck system that would meet the operational requirements and functional objectives of the 1990s commercial ACT airplane.

The details of this work are contained in References 12, 13, and 14.

#### 5.2.2.1 Advanced System Trade Studies

The classical approach of synthesizing one control loop at a time is not well suited to dealing directly and efficiently with coupled multiloop systems or to taking advantage of favorable interactions between the various control loops. This work developed control law and synthesis methods suitable for a coupled multiloop system, and demonstrated the potential benefits of these methods by evaluating closed loop performance of the resulting control laws. The methods used were based on modern optimal control and estimation theory. Control laws were synthesized for GLA, FMC, and rigid-body (quasi-static aeroelastic) PAS and command augmentation.

GLA and FMC control law performance was evaluated based on indicated wing load (approximate expressions of the load contained in the mathematical model) and control surface activity, both in response to continuous random vertical turbulence and in response to discrete vertical gust. PAS control laws were evaluated based on pitch-rate and load-factor response to elevator commands.

The ACT control law synthesis on a flexible transport airplane necessitates solving a coupled, multiloop control problem because of the complexity of the control task and the dynamic characteristics of the airplane. The design was accomplished using a set of experimental computer programs based on time-domain modern control theory, suitable for the analysis and synthesis of the multivariable controllers. Synthesis and analysis require dynamic models of the flexible airplane, the actuation system, and wind disturbances, as well as measurement equations for structural displacements, velocities, accelerations, bending, torsion, and shear. These models are connected to perform open-loop analysis, control law synthesis and, when combined with a control law, closed-loop performance evaluation. The airplane is represented at each flight condition by a set of constant coefficient, linear second-order differential equations with first-order lag terms. The optimal approach to ACT control law synthesis yielded

comparable control law performance much more systematically and directly than the classical S-domain approach. However, certain high-frequency gust-load alleviation functions may require increased surface rate capability as a result of these synthesis methods.

The procedures developed and tested in this work offer systematic methods for selecting proper control surfaces, actuation bandwidths, and sensor locations for specific ACT function performance. They offer a direct and systematic method of deriving multiloop control laws that satisfy the design requirements.

#### 5.2.2.2 Implementation Alternatives

This part of the Advanced Technology ACT Control System Definition Task was intended to identify an ACT system implementation based on component properties and characteristics expected to be available for a commercial airplane, circa 1990. The first phase of this work examined the technology developments for sensors, actuators, computer hardware, and computer software and projected that status to approximately 1990. During the second phase, three alternative systems with varying degrees of risk were defined and qualitatively evaluated. The final phase of the work consisted of selecting a "best" implementation of ACT for a commercial airplane of that era and performing reliability and cost-of-ownership analyses for that system.

The sensor survey addressed air data, attitude, angular rate, and acceleration sensors. It was concluded that air data should be obtained from the airplane's digital air data system. The attitude signals and cg acceleration are best obtained from the inertial reference system output signals. The ring laser gyro was recommended for angular rate sensors. The wing-mounted accelerometers should be piezo-resistive strain gages.

Developments in high-speed processing components are expected to lead to significant reductions in chip counts and connections. This, in turn, is expected to lead to a situation in which size, weight, and power requirements of the system's computers will no longer be a significant consideration.

Actuation concepts were reviewed and compared to the currently known requirements. It was concluded that, except for certain special-purpose applications (i.e., trailing

edge flaperons), conventional hydraulic actuation concepts should be applied to a 1990 design.

Three alternative advanced technology ACT system configurations, characterized as having low, medium, and high risk for a circa 1990 commercial application, were selected and are shown in Figure 24. The high-risk system (part (a) of the figure) capitalizes on recent and projected advances in self-testing digital circuitry and in integrated circuit technology. The computational element, consisting of four self-checking computer modules of multiple microprocessors, builds on the concepts used in the fault-tolerant multiple processor (FTMP) and software-implemented fault tolerance (SIFT) architectures. Each module is 100% self-checking and does not require cross-channel comparison. The computers run asynchronously, and the system relies on ultrareliable self-checking bus adapters and controllers.

The medium-risk system (fig. 24b) uses multiple microprocessors, operating asynchronously, in each computing channel. Serial digital data busing is used extensively for both sensor and actuator interfaces. The principal objectives of this design were to create more success paths for flight safety and dispatch reliability and to reduce software complexity and preparation costs.

The low-risk system (fig. 24c) follows the development of frame synchronized computers in the 1970s. Data are exchanged among the redundant computers by dedicated serial buses. Computations are identical among the computers. Sensor and servo interfaces are primarily analog, and only moderate technology growth is assumed. Key characteristics of the three systems are shown in Table 6.

A derivative of the medium-risk system was recommended as the 1990 ACT System. It uses redundant buses for sensor-computer and computer-actuator interfaces, with all sensor data available to all computing channels. Computing is asynchronous among channels and is compartmented so that separate microcomputers perform input/output processing, control law computations, and redundancy management. This avoids the monolithic software structure and results in lower cost for software design, verification, and validation. The sensors and actuators have self-contained electric power supplies and bus interface circuits. The crucial control laws computation mode is assumed by the I/O microcomputer if the control law microcomputer fails in that channel. This provides additional redundancy and reliability for crucial functions. The

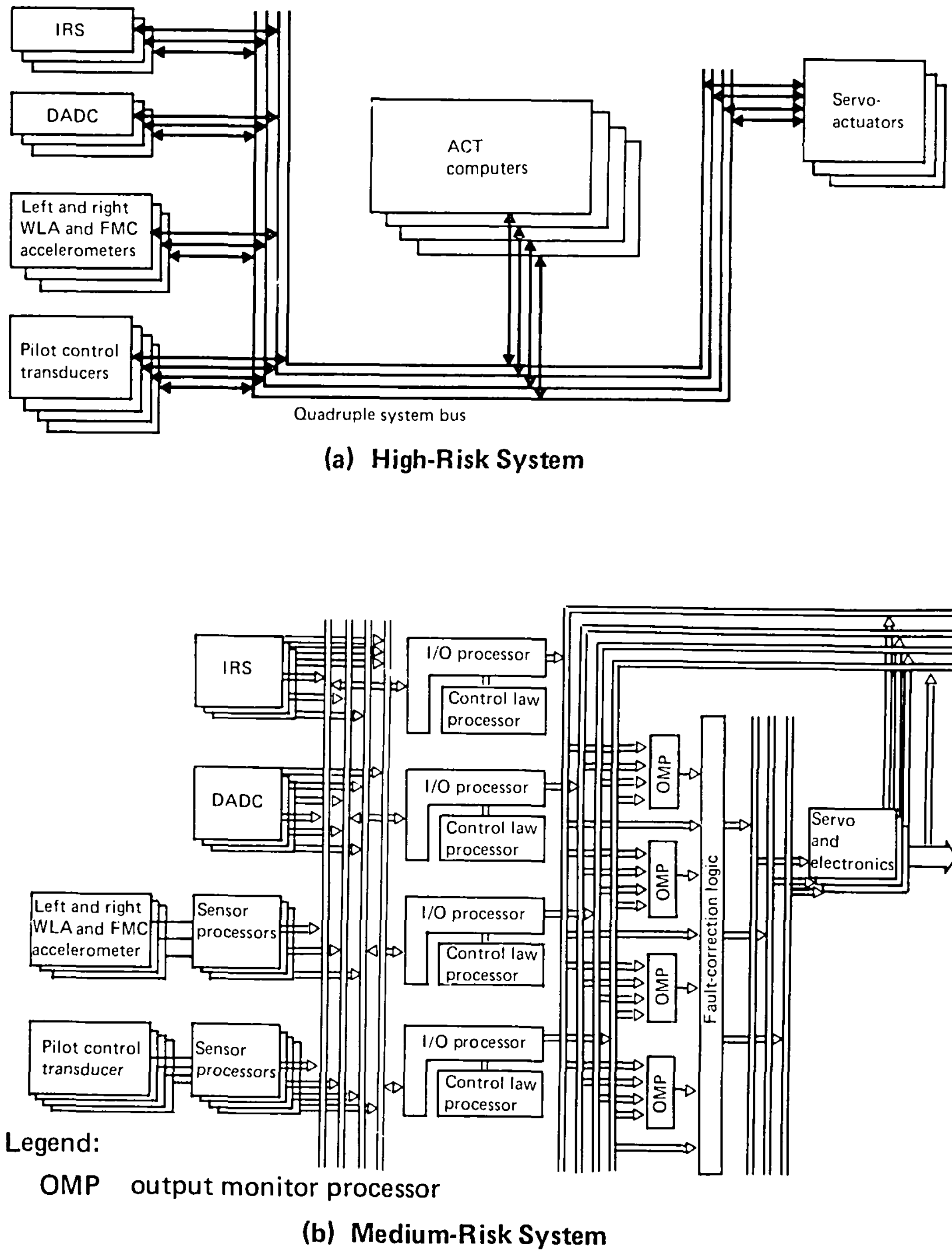



*Figure 24. Advanced ACT System Alternatives*

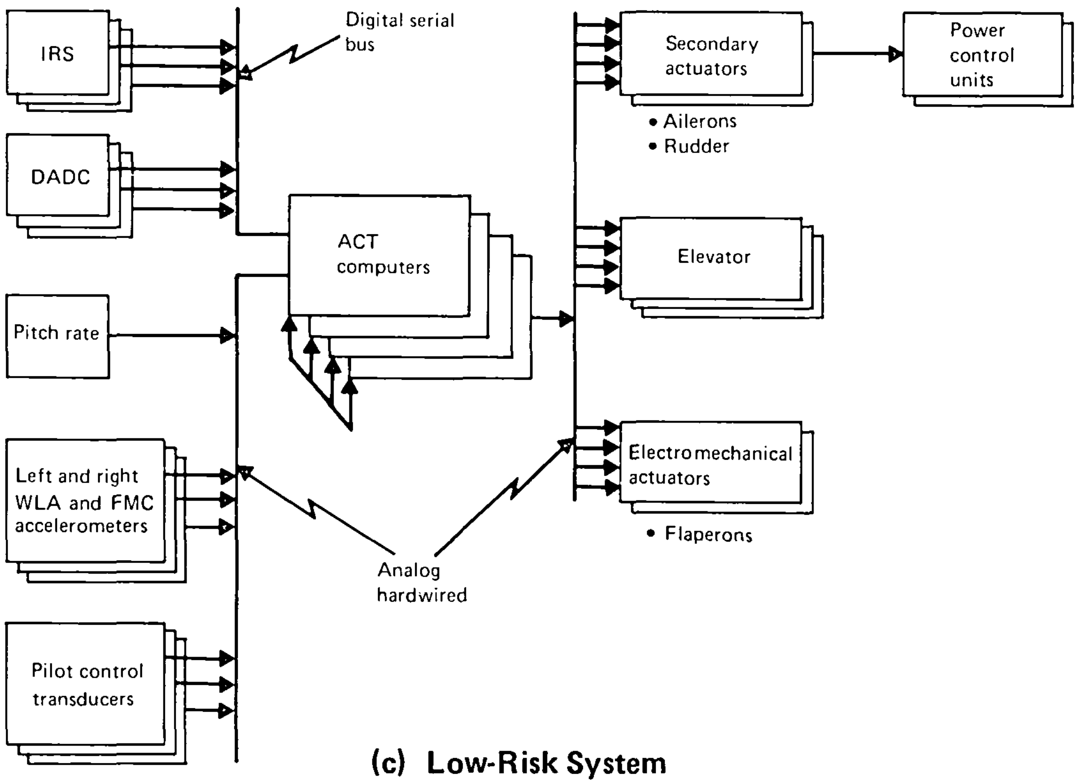



*Figure 24. Advanced ACT System Alternatives (Concluded)*

*Table 6. Alternative ACT System Comparison*

| Characteristics | System features | | |
|---|---|---|---|
| | Low risk | Medium risk | High risk |
| • Sensor set | • Three IRSs<br>• Three DADCs<br>• Three sets of accelerometers for WLA and FMC<br>• Four pilot input transducers<br>• One pitch-rate sensor | • Same as the low-risk system without pitch-rate sensor | • Same as the medium-risk system |
| • Sensor input approach<br>• IRS, • DADC }<br>• Others | • Serial digital bus to the ACT computer<br>• Hardwired analog to the ACT computer | • Serial digital bus to I/O processor | • On common serial digital bus |
| • Failure management<br>• Critical functions<br>• Crucial functions | • Majority vote and comparison monitoring<br>• Same with fourth pitch-rate sensor | • Same as the low-risk system<br>• Same with Luenberger observer to estimate q from vertical acceleration and other signals | • Same as the low-risk system<br>• Same as the medium-risk system |
| • Bus structure | • Two bus systems<br>• ARINC 429 from IRS and DADC to ACT computer<br>• Serial digital data exchange between computers | • Three bus systems<br>• Quadruple sensors to I/O processor<br>• Quadruple I/O processor to output monitor processor<br>• Triplex, output monitor processor to servos | • One universal quadruple bus system<br>• Self-checking |
| • Computer system<br>• Redundancy<br>• Architecture | • Quadruple<br>• Uniprocessors | • Quadruple<br>• Multimicroprocessors<br>• Sensor<br>• I/O<br>• Control law<br>• Output monitor<br>• Servo | • Quadruple<br>• Self-checking computing modules composed of multiple processors |
| • Synchronization | • Frame synchronized | • Asynchronous | • Asynchronous |
| • Failure management | • Self-check and bit-by-bit comparison monitor | • Output monitor processor, comparison | • Completely self-checking, no comparison |
| • Analog backup | • Yes | • No | • No |
| • Servos and actuators<br>• Servo loop electronics<br>• Command output approach<br>• Failure management | • In ACT computers<br>• Hardwired analog<br>• Monitored in ACT computer<br>• Hardwired fault correction | • In dedicated servo-microprocessor<br>• Serial digital buses<br>• Quadruple to OMP<br>• Triplex OMP to servo<br>• Monitored in OMP<br>• Fault correction via serial bus | • Incorporated in multiprocessor<br>• On common serial digital bus<br>• Monitored in ACT computer<br>• Fault correction via bus |
| • Software characteristics | • Complex, 1980 technology | • Simplified, segmented into microprocessors by function; reduced redundancy management required | • Simpler because of self-checking autonomous channels, highly reliable through advanced verification and validation |
| • Reliability assessment (probability of failure during 1-hr flight)* | • $4 \times 10^{-12}$ | • $< 10^{-12}$ | • Not assessed |

*Reliability assessment is for sensing and computation (actuation excluded) and assumes software reliability and coverage equal to 1.0.

1990 system is integrated. All functions are performed by each of the four ACT computers in the central set. Sensors and control surface actuators are shared between functions to the extent allowed by the control laws. The airplane's primary control is fly-by-wire, with all control surface actuators signaled electrically. The system architecture is shown in Figure 25.

The encouraging results of this control system development work emphasized the desirability of proceeding into specific system definition, design, laboratory tests, and flight test, as outlined in the IAAC Project Plan (ref. 2).

#### 5.2.2.3 ACT/CONTROL/GUIDANCE SYSTEM

This task was undertaken to understand the relationship of the ACT systems to the control, navigation, and guidance systems and to develop an appropriate functional integration within the anticipated operating environment of the 1990s. The first step was to define the expected air traffic control environment of the 1990s, the technology that was expected to be available for airplane system implementation, and the definition of system functions and their criticalities. Based on these definitions, an integrated ACT/Controls, avionics functions, and crew interfaces for the 1990s ACT airplane was established.

This ACT/Control/Guidance System study provided an opportunity to apply a systematic top-down design approach to the system design, generally unconstrained by preconceived notions of what the system architecture should be. System architecture alternatives examined included - among other aspects - backup systems providing degraded performance in lieu of the redundant, full-performance system; various ways of combining (or separating) processing functions; and such specifics as primary or secondary actuation and the control surface redundancy. Complete evaluation of these alternatives was beyond the scope of this work, but the study did lead to the identification of attractive system architectures.

The principal conclusions of the work are:

- A structured approach to hardware and software development is beneficial, and may perhaps be essential to future avionics system design.

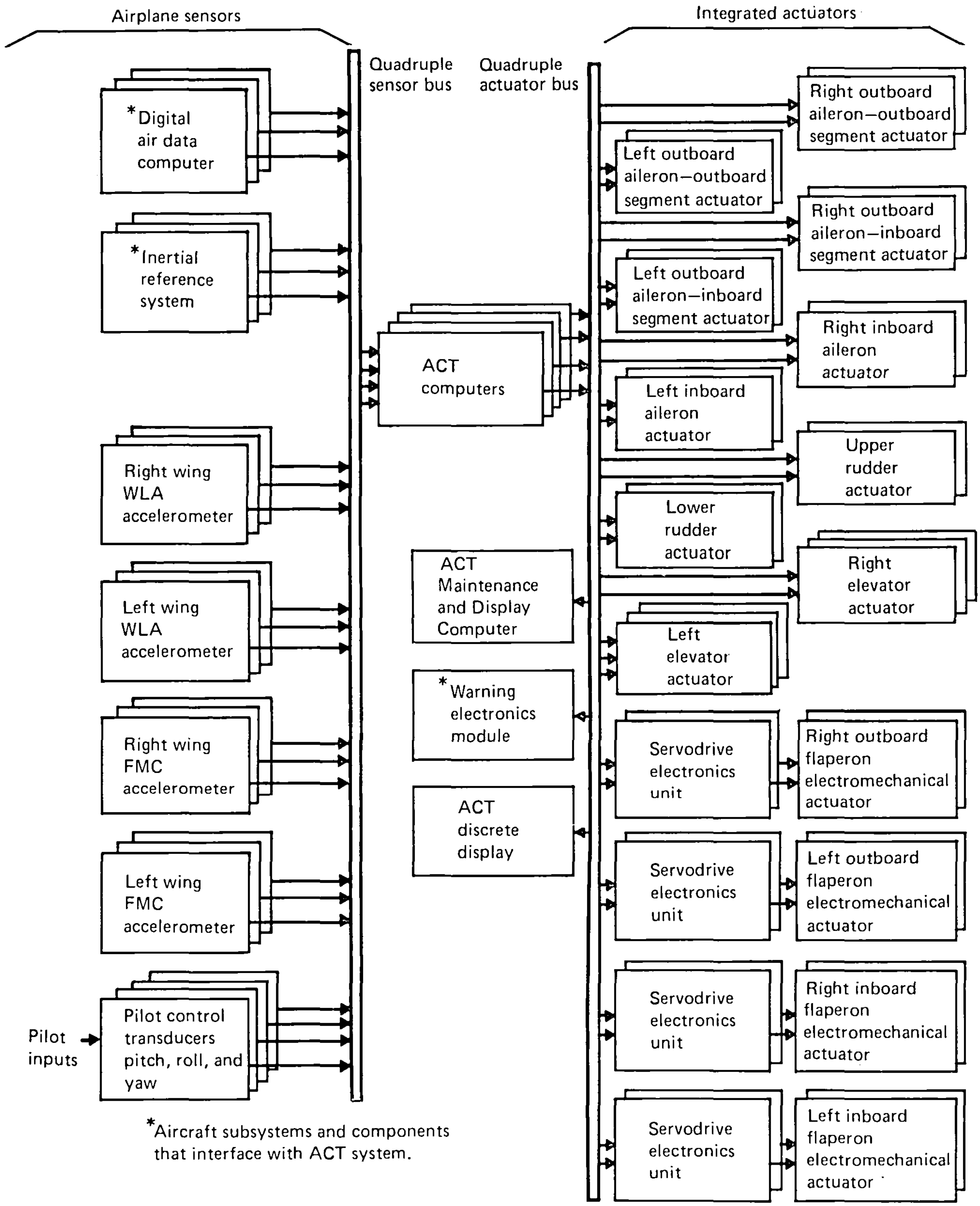



*Figure 25. 1990 ACT System Architecture*

- As the design progressed to each lower level, it was necessary to change some of the architecutral concepts, and several iterations were sometimes required to arrive at a final form.

- The integrated ACT/Control/Guidance system imposes no unusual constraints on flight operations and should not impact the anticipated air traffic control environment.

### 5.2.3 LONGITUDINAL HANDLING QUALITIES CONSIDERATIONS

A part of the third major IAAC Program Element, Test and Evaluation, was a piloted simulation evaluation of the longitudinal handling qualities of the airplane selected for flight testing the Test ACT System. Reduced stability levels and associated control laws were evaluated on a moving-base simulator, with the Boeing 757 as the modeled airplane. Using the revised Cooper-Harper Pilot Opinion Rating Scale (fig. 26), four experienced pilots, who were familiar with the 757, rated various 757 configurations for a range of flight conditions and cg locations. Two pitch-augmented stability (PAS) control law configurations were investigated: (1) a fixed-gain Essential PAS control law with pitch-rate feedback, and (2) a variable-gain Primary PAS with pitch attitude hold and pitch-rate feedback. The results reported here include the simulation study results and the way they correlate with existing handling qualities criteria. The details of the work are contained in Reference 15.

#### 5.2.3.1 Objectives

In support of Test ACT System development, the objectives of the piloted simulation task were to:

- Establish the cg range over which the unaugmented airplane is controllable.

- Determine a simple augmentation configuration that would satisfy the requirements of Essential PAS; i.e., produce Level 2 (minimum acceptable) handling qualities for an unstable airplane.

- Confirm the feasibility of obtaining Level 1 (good) handling qualities at extreme aft cg locations with the addition of Primary PAS.

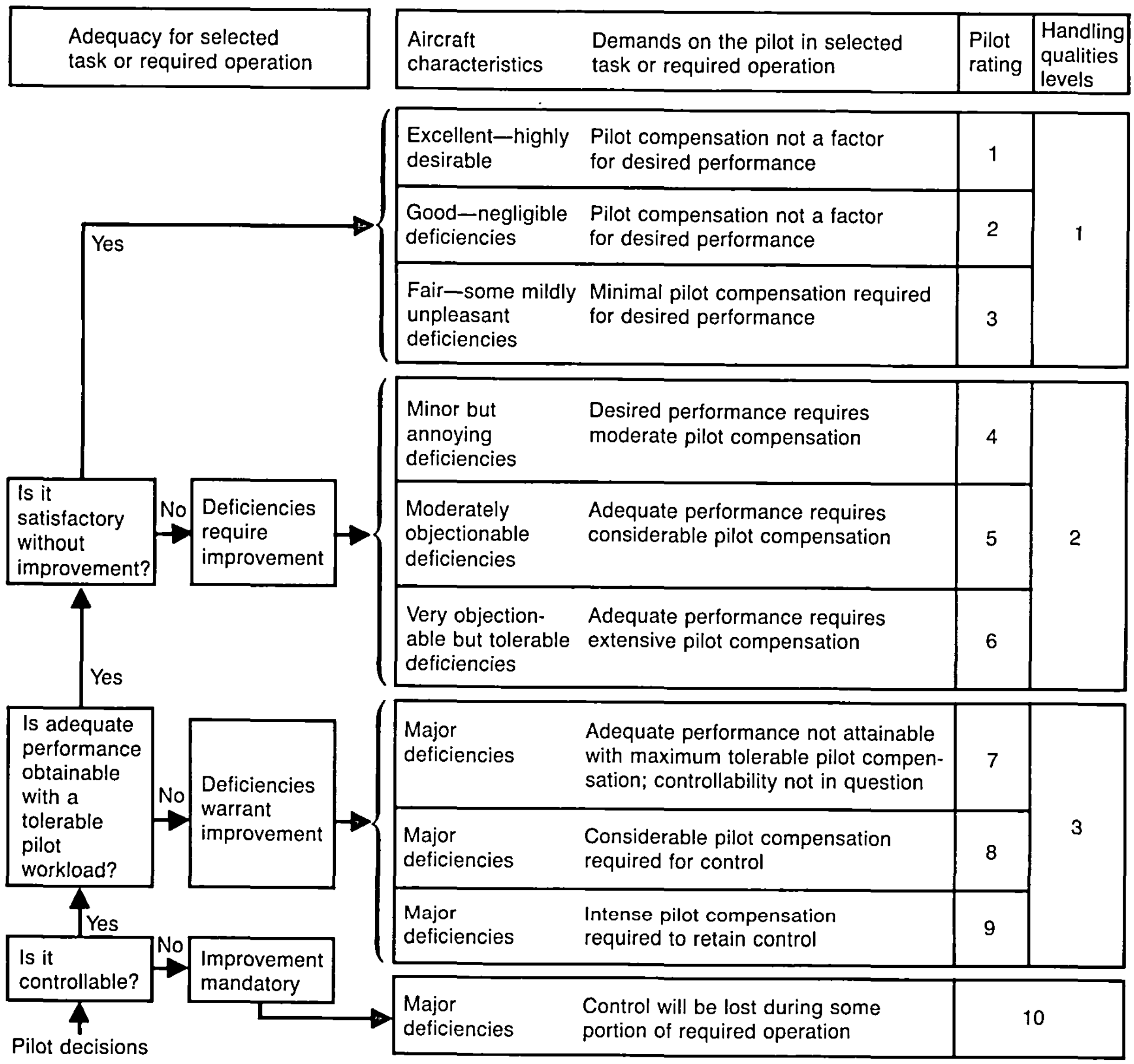



*Figure 26. Cooper-Harper Pilot Opinion Rating Scale*

- o Investigate alternative methods of integrating Essential and Primary augmentation systems.
- o Estimate authority requirements of selected configurations.

#### 5.2.3.2 Approach

This study used PAS concepts that were developed during the IAAC Wing Planform Study and Final Configuration Selection (ref. 9) and were modified for application to the Boeing 757 airplane. Performance and stability requirements, as specified in the IAAC design requirements and objectives (DRO), were used as guidelines. The simulation mathematical model was the 757 baseline. The unaugmented airplane model was evaluated at progressively aft cg locations to determine minimum controllability limits. Essential PAS was then tested and modified as necessary to provide acceptable handling qualities throughout the proposed flight test envelope. In addition, Primary PAS was developed and evaluated for good handling qualities.

#### 5.2.3.3 Results

The study results can be considered in three categories: the unaugmented airplane, the airplane augmented with an Essential PAS system, and the airplane augmented with a Primary PAS system. Essential PAS is intended to provide minimum acceptable emergency handling qualities for an unstable airplane with very high reliability so that there is no requirement for acceptable unaugmented characteristics. Primary PAS is intended to provide fully satisfactory handling qualities for the same flight conditions. For test purposes, the unaugmented airplane should also have controllable handling qualities at the nominal test conditions. Four Boeing experimental-test pilots who had previous simulation experience with the unaugmented normal cg-range characteristics of the 757 evaluated the airplane in terms of the revised Cooper-Harper Pilot Opinion Rating Scale.

Two principal flight conditions were simulated in detail. Maximum weight landing approach and midweight high-altitude cruise were selected as being representative of normal flight test conditions. Other conditions were spot-checked to verify that the results would be valid throughout the flight envelope. Ground stability and nosewheel steering were not addressed in this study.

As shown in fig. 27, for unaugmented landing approach, Level 2 (acceptable) handling qualities were attained at a cg of 57% MAC (6% aft of the neutral point). The Level 3 (unacceptable) boundary could not be established because the required cg was far aft of the trimmable cg range. For unaugmented cruise (fig. 28), Level 2 ratings were reported aft to 47% MAC (5% forward of the maneuver point). The Level 3 boundary is approached at cg locations of 55% to 60% MAC (or slightly aft of the maneuver point). Essential pitch-rate PAS provided pilot ratings that were very close to or within the Level 1 (good) boundaries. Primary PAS, although evaluated to a lesser extent than Essential PAS, yielded Level 1 pilot ratings in most cases. High-speed cruise, rather than landing approach, determines the flight aft-cg limit for the airplane. The study results correlated reasonably well with several existing handling qualities criteria. The study results were also found to be comparable to those reported by both the Douglas Aircraft Company and the Lockheed-California Company for simulation investigations of transport configurations with roughly similar dimensional and mass characteristics.

### 5.2.4 TEST ACT SYSTEM

Many of the technical issues involved with the implementation of ACT can be addressed through paper design of appropriate systems and analysis of the systems, as was accomplished in the work previously described in Sections 5.2.1 and 5.2.2. However, there is another class of problems and technical difficulties that can only be addressed by actually designing and building the equipment. Therefore, based on the work described above, a system architecture suitable for a major commercial application of ACT on a new airplane was defined and documented. The system details are contained in Reference 16.

The final objective of the IAAC Project was to reduce the risk of incorporating these advanced systems in a commercial airplane to a level commensurate with commercial practice, as far as possible within the funding constraints. In order to proceed into this final phase of the work, an ACT system that incorporated the most significant functions in an implementation architecture suitable for commercial application (designed to meet the reliability requirements) was selected as a subset of the system

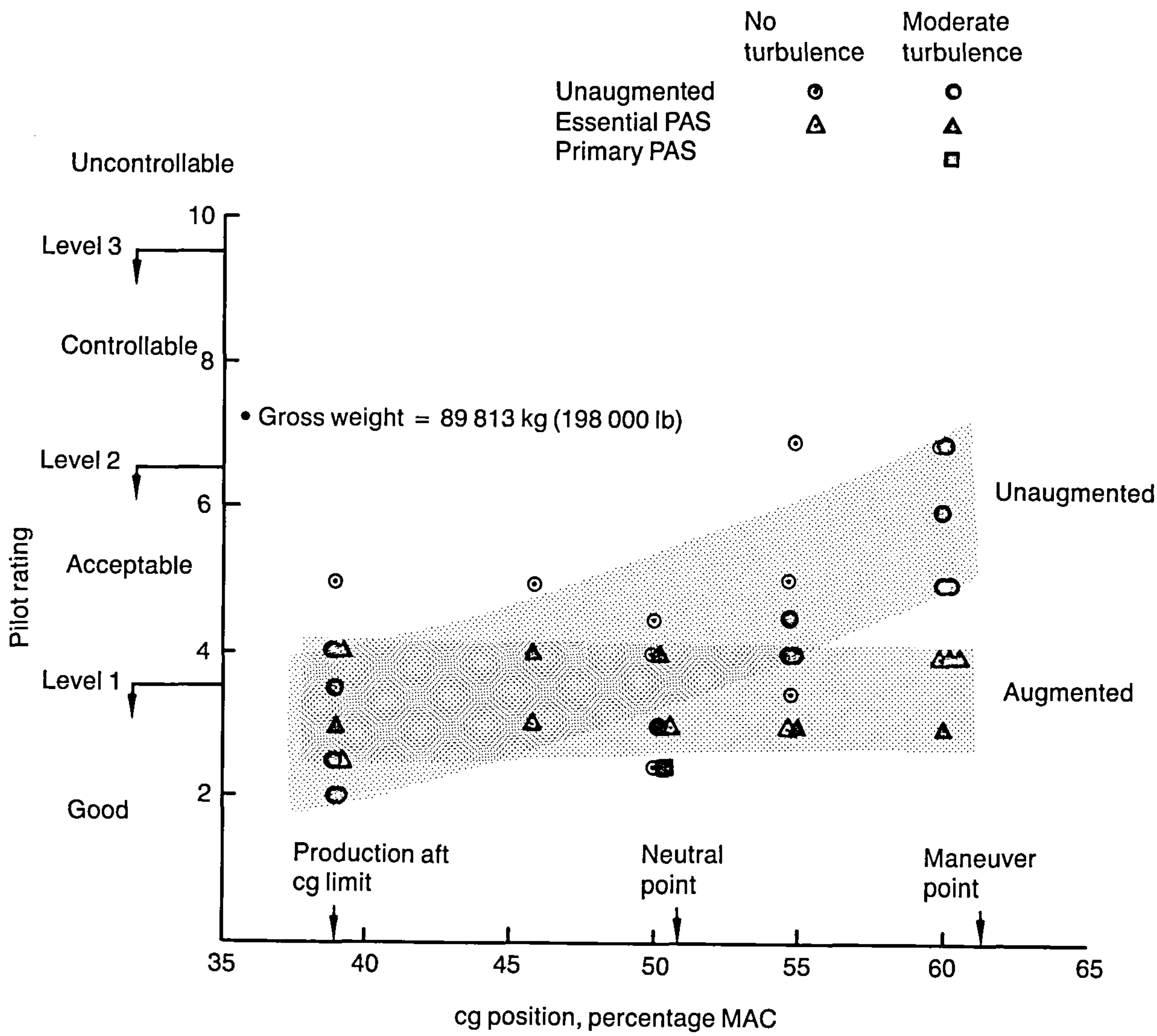



*Figure 27. Effect of Center-of-Gravity Position on Pilot Rating—Landing Approach*

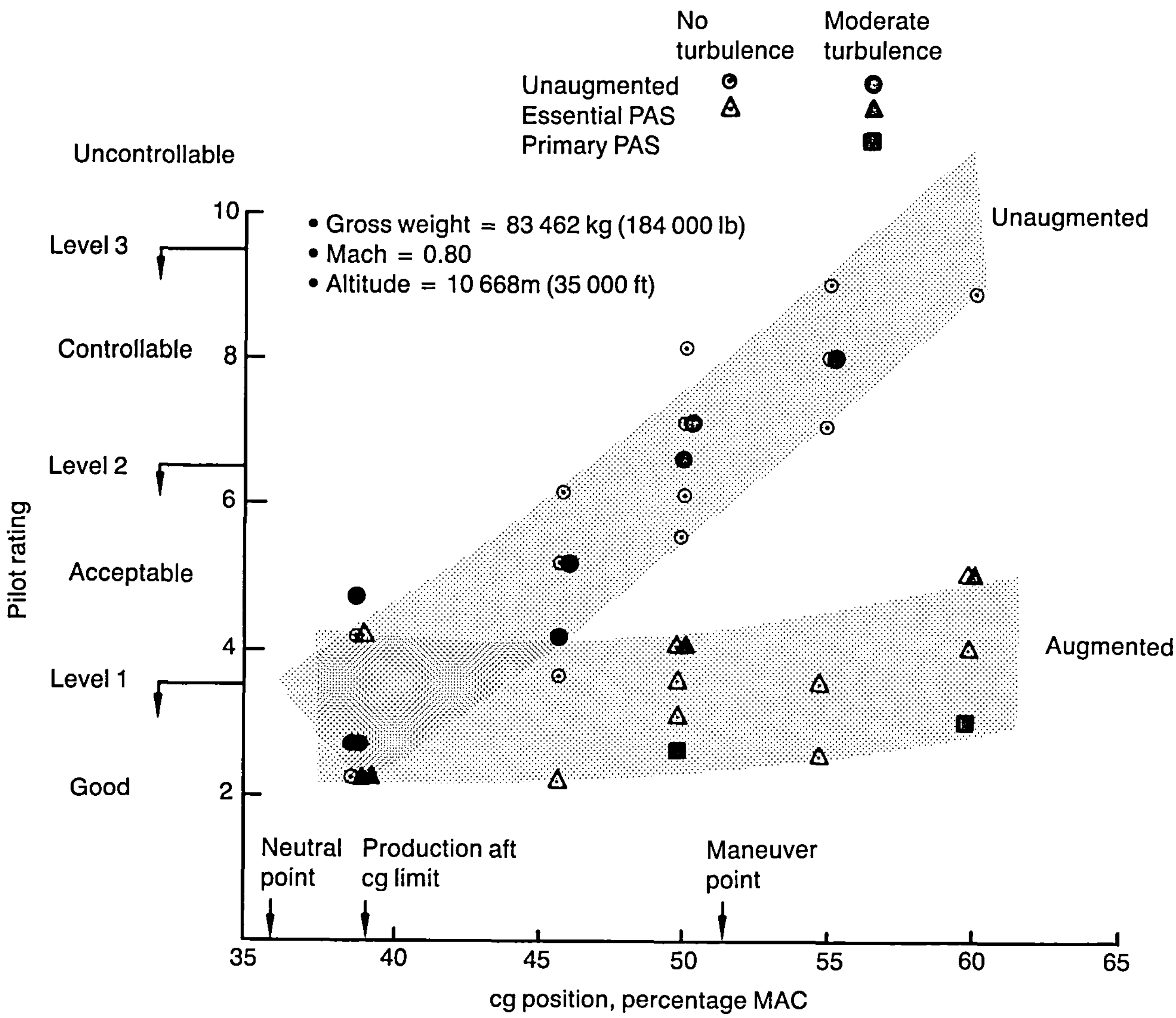



*Figure 28. Effect of Center-of-Gravity Position on Pilot Rating—Cruise*

described above. That system is called the Test ACT System. The system requirements that drove the design on the Test ACT System fabrication and testing that was accomplished are discussed in this subsection. More detail is presented in References 17 and 18.

### 5.2.4.1 Requirements

Early in the Test ACT System task, system requirements were established to govern the engineering work. The first, and possibly the most significant, requirement was that the system was to be designed and built so that it could be test flown. This, in turn, required the selection of a "host" airplane for the potential flight test. The requirements included a statement of required reliability and dispatchability, and limitations on the magnitude of modification that would be allowed on the proposed test airplane.

The ACT system functional requirements are summarized as follows:

- The Pitch Augmented Stability (PAS) function shall enable flight with Level 1 flying qualities throughout the flight envelope and the design cg range.

- The wing load alleviation (WLA) function shall reduce wing loads due to either or both controlled maneuvers and atmospheric disturbances.

The failure survival of the Test ACT System must meet the requirements of FAA Advisory Circular 25.1309b (ref. 7). A summary is shown below:

- Any condition that can prevent the continued safe flight and landing of the airplane shall be extremely improbable. Probability of such a condition will be shown to be less than $10^{-9}$ during a 1-hr flight.

- The occurrence of any other failure condition that can reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions shall be improbable. Such a probability will be shown by analysis to be less than $10^{-5}$ during a 1-hr flight.

- No single system failure shall preclude continued safe flight and landing.

In addition to these certificatory requirements, a set of specifications and ground rules was imposed on the system design to ensure that the resulting system would be compatible with a potential commericial application. That is, the system shall include an automated preflight test that determines dispatch status of the system (in less than three minutes) and indicates it to the crew, and system faults detected by automatic tests shall be automatically stored in a nonvolatile memory for later recall. The system specification also contained special test provisions and certain requirements that stemmed from the plan to install the test system in an existing 757 airplane.

The design and fabrication of the Test ACT System was governed by the requirement that the materials and processes used in building the system were consistent with those approved for use in the 757/767 systems. A more comprehensive discussion of system requirements is contained in Reference 17.

#### 5.2.4.2 Architecture

The Test ACT System was to mechanize the flight-critical* pitch axis stability augmentation and FBW longitudinal control, WLA, speed stability augmentation, and elevator offload functions. The flight-critical function had to have a probability of total function loss less than $10^{-9}$ in a 1-hr flight. The balance of the functions had to exhibit a probability of function loss less than $10^{-5}$, also in a 1-hr flight. These considerations led to the identification of the following architectural issues:

- o What redundancy management plan, system elements, and interfaces will serve to achieve a probability of function loss less than $1 \times 10^{-9}$ in a 1-hr flight?
- o What redundancy level is required to preserve airline schedule reliability?
- o What system architecture will minimize susceptibility to generic hardware and software faults?

* Current FAA notation, see Table 3 for the relationship to the IAAC notation used in the previously published documents and elsewhere in this document.

- o What monitors can be allowed to shut down a flight-critical function channel?

- o Assuming a two-level system composed of Primary and Essential computer sets:

- o What monitors can be allowed to shut down a flight-critical function channel?

- o Assuming a two-level system composed of Primary and Essential computer sets:
  - o Is switching between levels allowable?
  - o In which level is preflight test performed?
  - o Are both levels full-authority?
  - o How should the flight critical part be implemented?
    - Digital or analog?
    - Cross-compared or brickwalled?
    - Dedicated sensors or shared sensors?
  - o Can gain variation be allowed in the Essential set?
  - o Should digital computer operation be synchronous or asynchronous?
  - o Should preflight tests be automatic or require manual intervention?
  - o How many voting planes should there be, and where should they be located?

Early in the IAAC Project it became clear that systems designed to meet the stringent requirement for probability of function loss less than $1 \times 10^{-9}$, and that also contained less critical functions, should be partitioned by criticality. This functional partition principle was applied to the Test ACT System, thus ensuring that a less critical function could not compromise the safety of a flight-critical function.

The Test ACT System architecture initially selected (fig. 29) used a digital Primary element and an analog Essential element. The digital Primary System consists of the airplane sensors (including the airplane's digital air data and inertial sensors) shown at the left of the figure, plus the wing accelerometers, the quadruple Primary digital computers, and the airplane's trim system. The Primary computers are microcomputers derived from the Collins FCC 701, the Autopilot/Flight Director System computer for the Boeing 757/767 airplanes. These computers operate asynchronously. The Primary System's throughput and memory capacity enable it to accomplish the following functions:

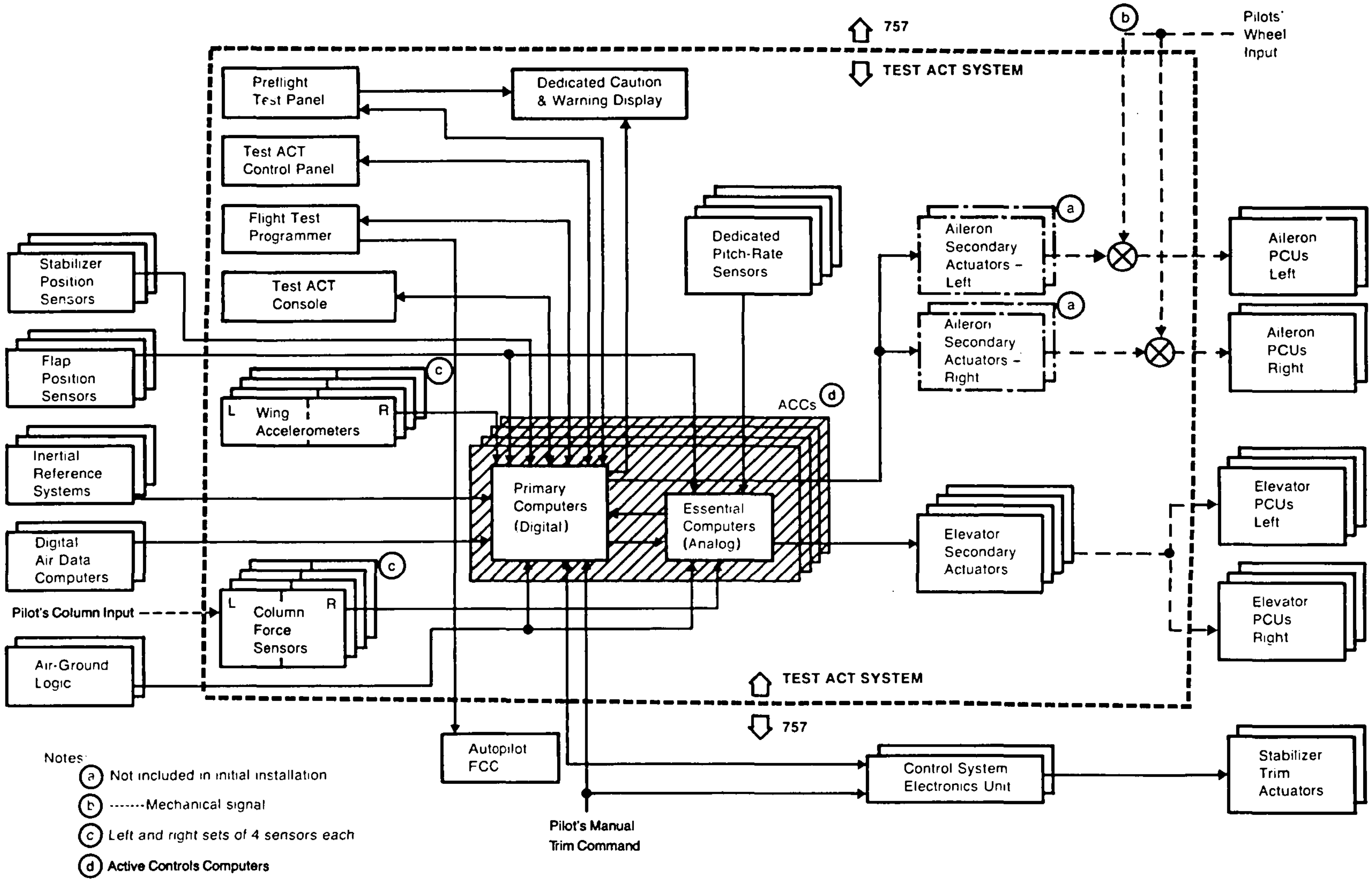



*Figure 29. Test ACT System Architecture*

- Primary system redundancy management and reconfiguration control.

- Preflight test of the complete Test ACT System, including the associated Essential channel.

- Self-test and self-monitor functions.

- Cross-strapped sensor signal selection and failure detection.

- Flight crew communication and control via three flight deck control panels.

- Simulated maintenance interface via the Test ACT console.

That part of the Test ACT System that must perform with extremely high reliability, as discussed in the preceding paragraphs, is called the Essential System. This element of the Test ACT System consists of the dedicated, quadruple-column-force sensors, dedicated pitch-rate sensors, the four Essential analog computers, and the four force-summed elevator secondary servos. This is a quadruple, simple, brickwalled, highly reliable system that provides acceptable airplane pitch axis handling qualities without relying upon the digital Primary System. The FBW function is provided by the column-force sensors and a simple, dual-gain, feed-forward control law in the Essential analog computers that command the elevator secondary servos. Short-period pitch stability augmentation is provided by the pitch-rate gyros and a simple dual-gain feedback control law. In normal operation these commands are supplemented by the Primary System commands to provide Level 1 flying qualities in pitch. If the entire Primary System fails, the Essential system provides adequate flying qualities for continued safe flight.

This Test ACT System architecture passes all elevator commands through the Essential System. The Essential System limits the Primary System commands to a safe level. Any potentially hazardous digital system elevator deflection command, i.e., one resulting from a fault in the Primary System software, is limited to a safe level by the hardware-implemented limiters in each of the Essential System analog

computers. The error-free software risk issue is thus addressed by a simple hardware feature.

### 5.2.4.3 Hardware and Software

The Test ACT System was designed by an integrated engineering team drawn from the Preliminary Design department of Boeing Commercial Airplane Company and the Collins Air Transport Division of Rockwell International. The system was fabricated by Collins. Beginning in November 1981, these organizations accomplished the following:

- Finalized the system architecture and selected the test airplane.
- Designed and analyzed the control laws and tested them by piloted simulation.
- Designed, fabricated, and bench-tested the computer hardware (digital and analog).
- Designed, integrated, and verified the digital system software.
- Selected and procured the system sensors.
- Designed modifications to the test aircraft, adding redundant secondary servos for elevator position commands.
- Developed the FBW direct drive valve system architecture.
- Designed, acquired, and bench-tested the DDV and actuator.
- Planned laboratory and flight test programs.

The end product of this work is a flight-worthy active controls system composed of pitch-augmented stability, pitch fly-by-wire, and wing-load alleviation, including both maneuver-load control and gust-load alleviation, for potential flight test on the Boeing

757-200 flight test airplane. The Test ACT System is housed in a console (fig. 30) designed for installation on the main deck of the 757. The Test ACT console contains all the control system electronics and the equipment for controlling and communicating with the system, both in the laboratory and for flight test operations. The console is shown in the laboratory configuration in the figure. The three flight deck panels are installed at the upper right in console No. 1. The Active Control Computers (ACC) occupy the left half of console No. 2. The balance of the equipment shown provides the means to monitor system conditions, load and read software, simulate faults, control power supplies, and conduct test operations.

The bulk of the equipment shown in Figure 30 is associated with test of this system. Figure 31 illustrates the equipment that actually performs the ACT/FBW functions (the wing accelerometers are not in the photograph). The four boxes house the digital Primary and analog Essential computers. Each box has both an analog and a digital section. The flight deck control panels are shown resting on the computers. The air-bearing pitch-rate gyros are immediately in front of the computers, with the quadruple column-force sensors immediately in front of the gyros. Figure 32 is a close-up photograph of the flight deck control panels. The center panel is a test panel only; a commercial design would not have such an element.

This system was designed to be test flown in the 757. Figure 33 schematically shows the elevator control system part of the Test ACT System as it was planned for implementation in the airplane. Note that the FBW control path was provided from the first officer's side by disconnecting the righthand column from the cable system and installing a mechanism that contains the quadruple-column-force sensors, dampers, and a feel spring. The electric commands from the ACCs control the ACT servos shown at the bottom of the figure. The four servos are force-summed, and the single command is passed mechanically to the righthand and lefthand elevator power control units. Figure 34 illustrates the planned placement of Test ACT System components in the 757.

In the final year of the IAAC Project, it became clear that the project would probably be truncated short of flight tests due to funding limitations. NASA and Boeing mutually agreed that the remaining part of the laboratory testing should be deferred in favor of making the Test ACT System available for alternate studies. The design,

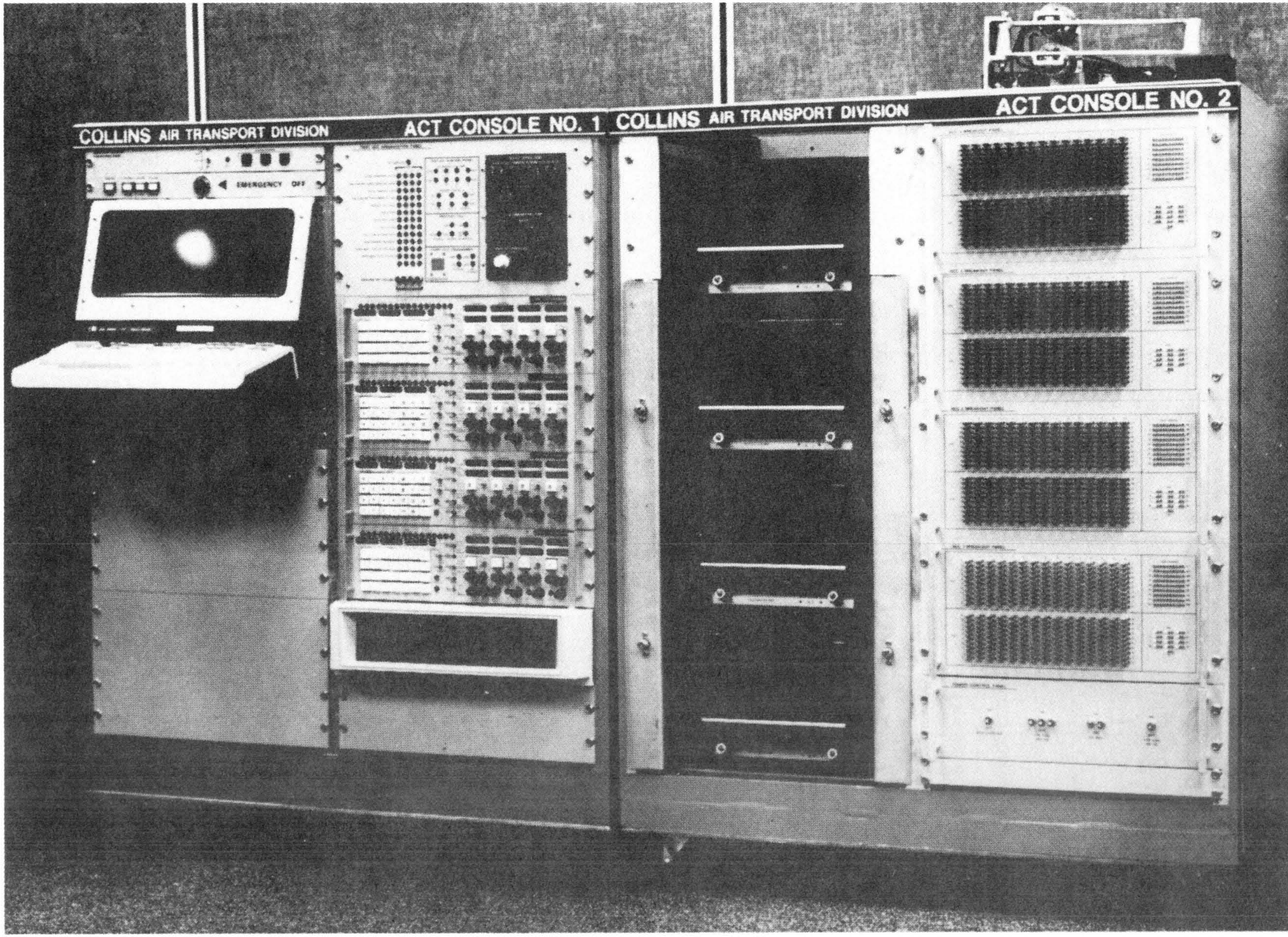



*Figure 30. Test ACT System Console*

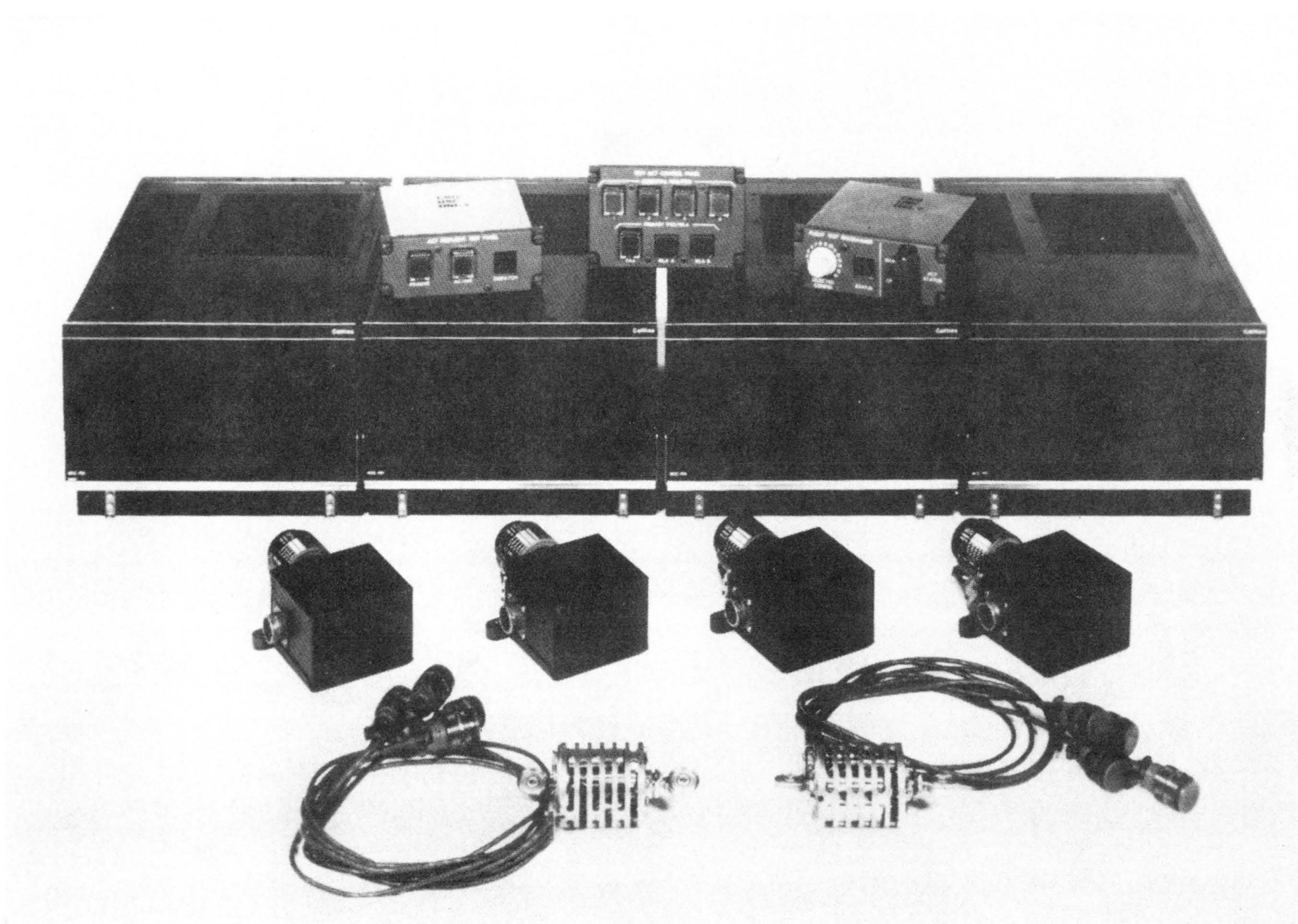


Figure 31. Test ACT System Electronic Hardware

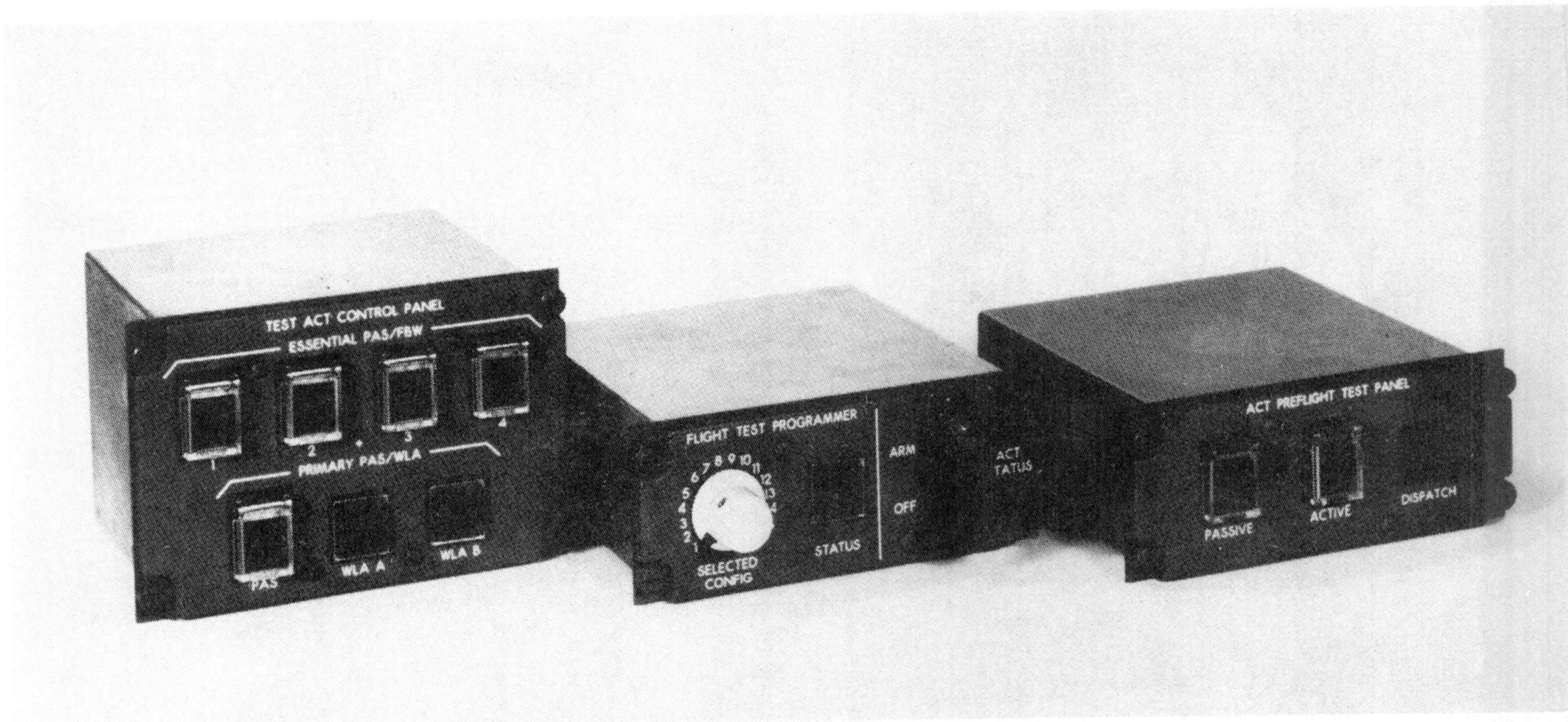



*Figure 32. Test ACT System Flight Deck Control Panels*

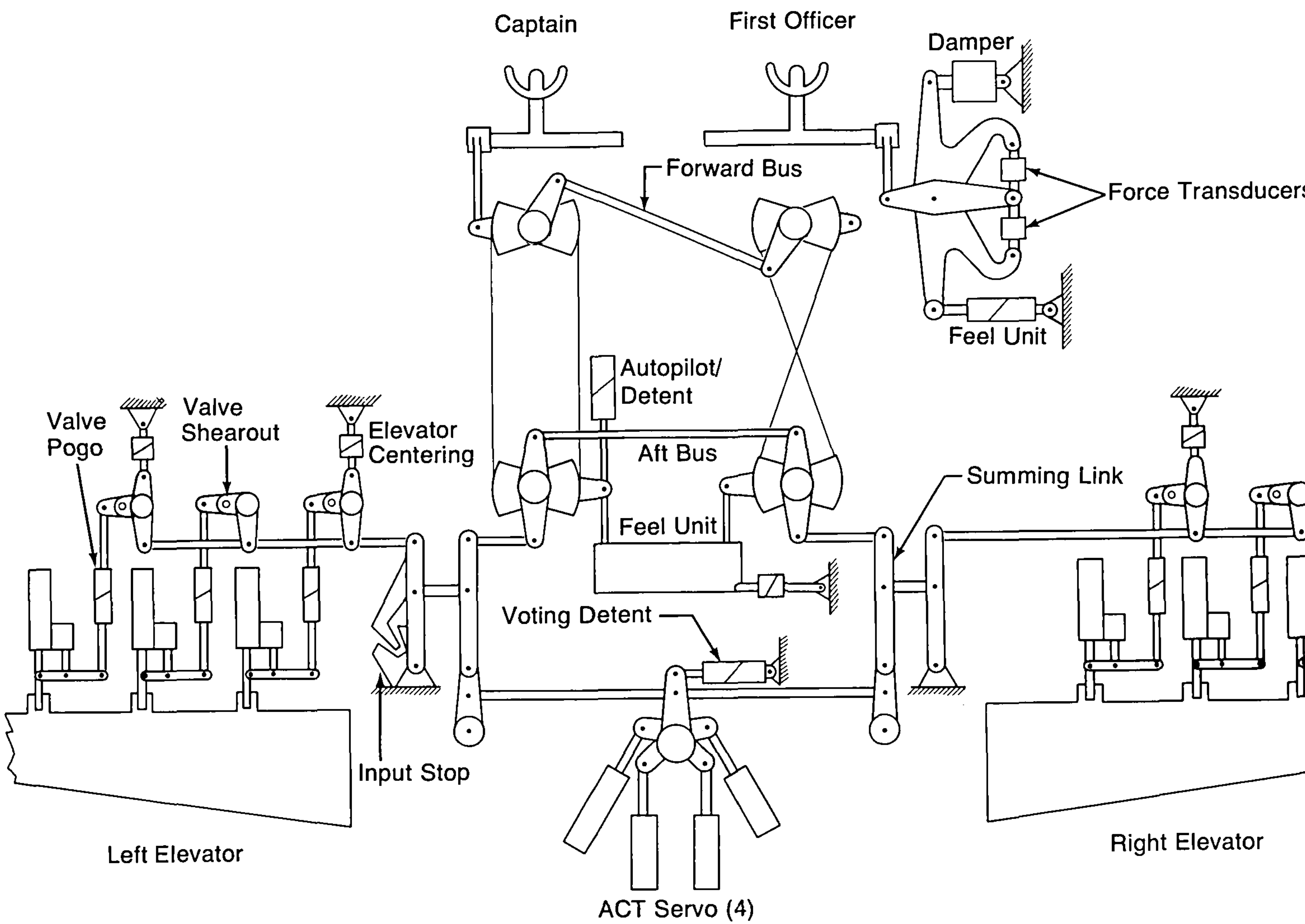
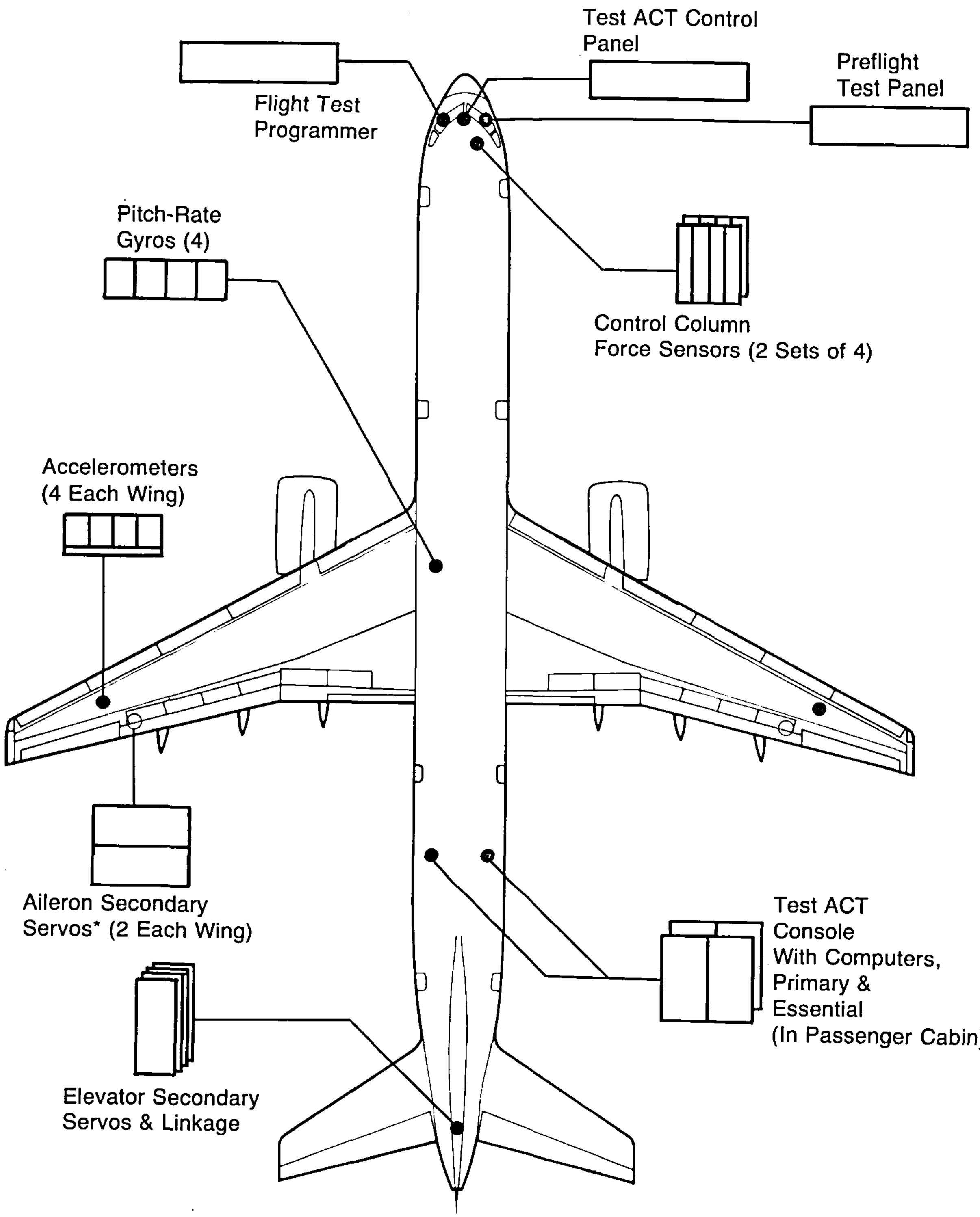



*Figure 33. Test ACT System 757 Elevator Control Schematic*




*Not part of initial installation

*Figure 34. Test ACT System Component Placement—757 Flight Test*

fabrication, and testing of a new-technology FBW actuation system was selected. Whereas the Test ACT System, as originally conceived, incorporated a force-summed secondary servo approach, the new actuation system incorporated a direct drive valve (DDV) with a different interface between the Test ACT ACCs, as shown in Figure 35. Note that the DDV concept electrically interfaces each elevator with the ACCs separately, resulting in a much simpler mechanical interface between the computers and the power control units. Figure 36 shows the DDV installation in the DAFCL. This is a change in redundancy management and remains to be thoroughly proven.

All Test ACT System Primary control laws, built-in tests, and digital system redundancy management are implemented in software. The primary software performs seven major functions: executive, control law computation, Primary System redundancy management, fault detection, flight deck interface, Test ACT Console outputs, and test option control. Approximately 16,000 words are required to accomplish these functions. Figure 37 illustrates the distribution of the final software among these seven functional areas. Note that, since fault detection could also be considered part of redundancy management, this system safety function requires 77% of the total software. The control laws, which are the reason the system was designed, require only 5% of the software. This is considered representative of these types of flight critical systems. All of the software was developed under Univac's EXEC-8 operating system on a Univac U1100 system located at Rockwell's Scientific Computing Center in Seal Beach, California. The Test ACT System software was written in the ALGOL Extended for Design (AED) language, a descendant of ALGOL-60.

#### 5.2.4.4 Verification and Validation

System verification is the process used to determine whether or not the Test ACT System met the system requirements as specified prior to and during design and fabrication. The verification process used on the Test ACT System consisted of five procedures: analysis, inspection, software verification, unit acceptance tests, and system acceptance tests. Analytical methods were used to verify reliability, dispatchability, safety, channel equalization, environmental impact, and flight-worthiness. The last two were based largely on the similarity between the Test ACT System

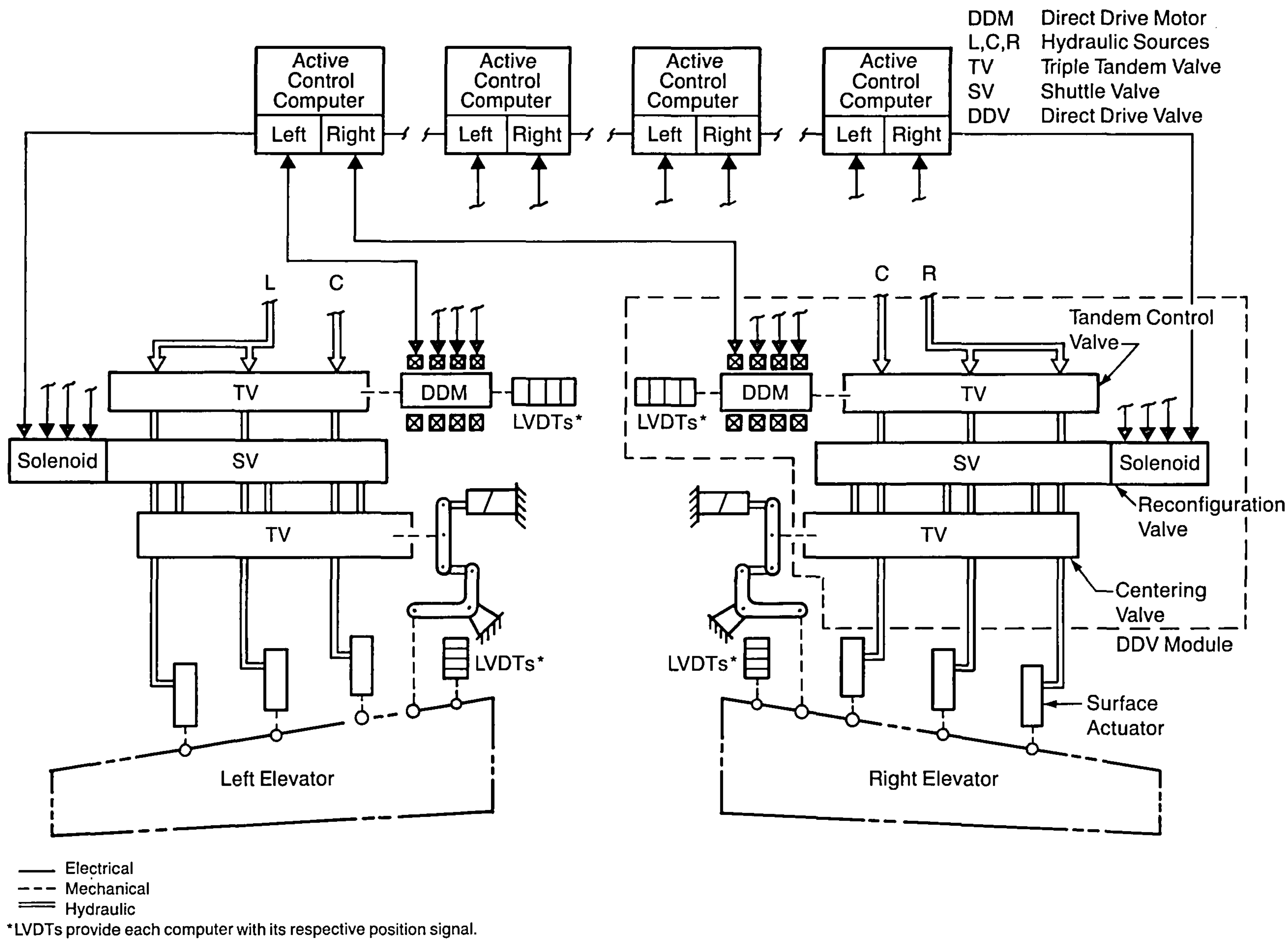



*Figure 35. Test ACT System—Direct Drive Valve Actuation Concept Diagram*

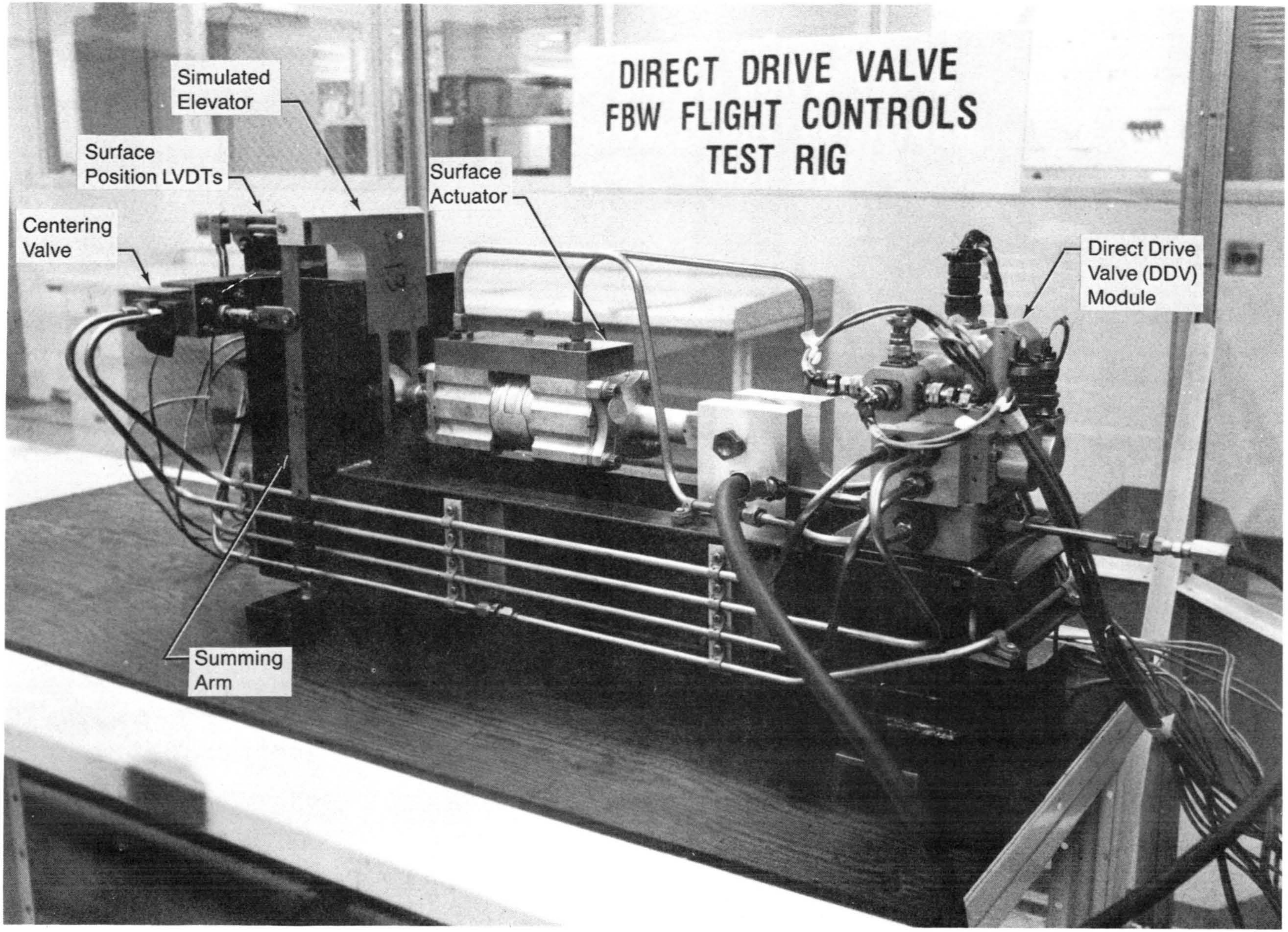



*Figure 36. Test ACT System Direct Drive Valve Test Rig*

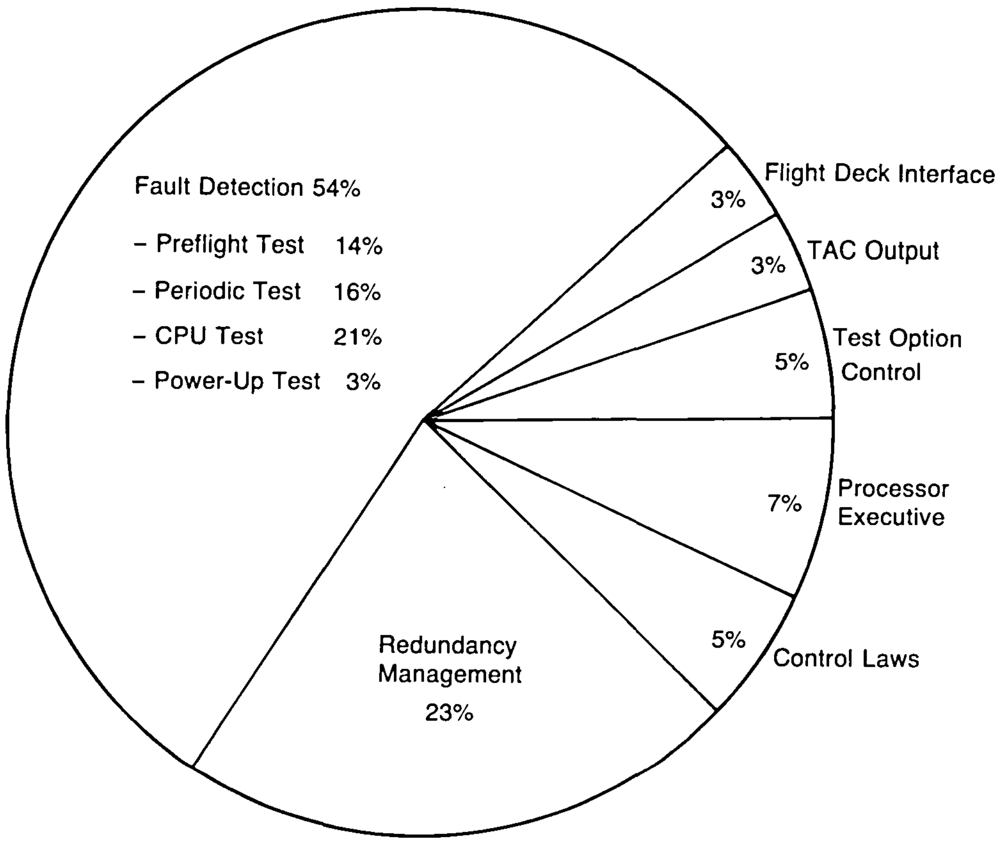



*Figure 37. Test ACT System Software Distribution*

components and the 757/767 Autopilot/Flight Director System equipment. The hardware was inspected at appropriate points in its manufacture by quality assurance representatives of both Collins and Boeing.

Software verification utilized three procedures: design walkthroughs, code inspections, and analysis of system acceptance test coverage. These augmented the ACC software verification obtained in the system acceptance tests. The unit acceptance tests were performed on selected line replaceable units of the system. This testing applied to the active controls computers (ACCs), the pitch-rate gyros, the preflight test panel, and the wing accelerometers. The system acceptance tests provided verification of the other line replaceable units. These final tests at Collins emphasized end-to-end testing and were based on easily observed system effects; i.e., servo disconnects and annunciations. Measurements were limited to those that could be made through the Test ACT console breakout panel (access to all the pins of the ACC rear connectors) and the Collins test adapters (access to the transfer buses). Fault insertion consisted of power interrupts, disconnects of equipment cables, simulated interface faults, and simulated processor faults.

System validation is the process of showing that the system requirements were correct, that the resulting system yields the desired performance, and that the system is safe for flight. The verification process occurred principally at Collins, where the equipment was designed and built. The validation process occurred at Boeing Commerical Airplane Company facilities, and included laboratory testing in the Digital Avionics Flight Controls Laboratory. The laboratory test categories were: open-loop hardware tests, open-loop software tests, failure detection tests, system integration tests, closed-loop system performance tests, and closed-loop failure response tests.

The system was installed in a workstation at the Boeing Digital Avionics Flight Controls Laboratory. The first activity was the integration of the Test ACT System into the laboratory. The validation testing began with hardware and software open-loop testing. The analog Essential computer was initially tested as a single channnel. Increasingly complex validation then progressed with multiple channels, the digital Primary computers, and an airplane simulation. It continued with performance testing of the ACT system electronics. In the last test phase, the control system was

modified and coupled to an actuator controlled by a direct drive valve. The test results of the Test ACT system validation are contained in Reference 18. If the NASA funding had allowed the testing to continue, it would have included a piloted simulation phase, using a simulator flight deck with the actual Test ACT Control Panels installed, a moving base cockpit, and computer-generated imagery. The next phase would have been a series of iron bird tests, and then flight tests.

The laboratory tests of the Test ACT System included all the hardware tests and the major open loop software tests. All major functions worked well, with only 33 problem reports generated. Two of these problem reports were major (when considered from the point of view of a production system, but not from the point of view of a test program), and dealt with the power supply. In summary, the system met all requirements that were examined in this truncated test phase.

# 6.0 REFLECTIONS

## 6.1 AIRPLANE DESIGN TEAM

The IAAC Project provided an arena for determining the necessary approach to the design of a commercial ACT transport configuration, as well as the performance and economic benefits of applying ACT to the airplane. There is, of necessity, a very large amount of coordination within an airplane design team. Traditionally that coordination occurred at the "results" level, i.e., when one engineering group had completed their design/analysis, they passed their results to the other groups that needed the data. Including ACT early in the design required that this process be reexamined. As a result, it was determined that integration of the engineering design process required that the analyses be coordinated, and where possible be accomplished from common data bases. In some instances, e.g. the development of flutter suppression or mode control functions, the structural dynamicist and the controls engineer needed to use common or integrated tools. During the ACT Airplane design phase, the IAAC Project demonstrated that a relatively small, closely knit, multi-discipline team, operating without the traditional organization boundaries, can examine alternatives and carry the design forward in a very efficient manner.

## 6.2 AIRPLANE BENEFITS OF ACT

An examination of the ACT airplane design results published under the IAAC Project will quickly show that the specific benefits of incorporating ACT into the design are dependent upon the airplane configuration and the mission it is being designed to serve. However, one ACT function is clearly more beneficial to a commercial transport airplane than any other: the pitch augmented stability (PAS) function. Incorporating this function into the design yields the largest benefit to the airplane performance of all those considered. Further, the benefit of PAS is largest for a long-range cruise airplane, but is significant for any range. The remaining ACT functions examined exhibited benefits that were generally smaller than those for PAS and were extremely sensitive to the specifics of the airplane configuration. For example, the Initial ACT Airplane configuration beneficially included flutter mode control (FMC) to provide flutter-free operation beyond the $V_{MO}/M_{MO}$ boundary, while the Final ACT Airplane configuration did not benefit from FMC. The most significant difference between the two designs was the flutter frequency.

Fatigue, flutter, and discrete gust design requirements tend to limit the benefits of incorporting WLA systems on short to medium-range, high-aspect-ratio, metal-wing airplanes. Systems capable of providing discrete gust load alleviation, significant fatigue load reduction, or flutter suppression tend to be complex, heavy, and costly. Further, such systems may impact the availability and dispatchability of the resulting airplane. They have not been shown to be generally beneficial, and in certain applications may not even be feasible for commercial airplanes. In contrast, long-range airplanes with high wing loading that are primarily maneuver-critical, with little or no fatigue or flutter penalty, are most likely to benefit from simple WLA systems. Applications of these types of systems show very significant promise for gross weight growth derivatives of such airplanes. The synergistic benefits of combining WLA with graphite-epoxy wings may show favorable benefits, but require considerable further analysis.

## 6.3 ECONOMICS OF AN ACT AIRPLANE

The economics of a new commercial ACT airplane will be extremely sensitive to the nonrecurring cost of developing and certifying the ACT systems with the required reliability/availability. This is a factor that can only be determined when the system requirements and architecture have been established and the costs associated with its development have been determined from building and certifying the system. Until then estimates must be relied upon. The results of this project suggest that such airplanes will be economically viable.

## 6.4 ACT AIRPLANES IN THE FUTURE AIR TRAFFIC CONTROL SYSTEM

An analysis of ACT airplanes operating in the expected 1990s ACT environment led to the conclusion that, under normal operation, an ACT airplane is expected to be totally transparent to the air traffic control system. Any system failure that significantly diminishes the airplane operability - whether due to an ACT or other system failure - may result in special requests of air traffic control like failures in any of today's systems. The future air traffic control environment will probably require increasingly complex avionics systems to take maximum advantage of the available capability. An ACT Airplane should fit into this environment as well or better than a more conventional airplane.

## 6.5 CONTROL LAW DEVELOPMENT

The complexity of the ACT control task and the dynamic characteristics of a typical flexible transport airplane dictate the solution of a coupled multiloop control problem. The classical approach of synthesizing one loop at a time is not well suited to dealing directly and efficiently with coupled multiloop systems; nor is it suited to taking advantage of favorable interactions between the control loops. During the course of the IAAC Project, control law synthesis was accomplished using both this classical approach and an approach based on time-domain modern control theory. The optimal controller, designed as an integrated multiloop controller, typically exhibited equal or better performance (airframe damping, or load reduction) than the classically designed system, with less surface activity. The implementation of such optimal control laws could affect the memory requirements and/or throughput of the ACT System computers. Consequently, the performance benefits would have to be weighed against the implementation impact.

## 6.6 CRITICAL SYSTEMS DEVELOPMENT

The criticality level that the system is designed to meet - whether flight critical or essential per (FAA notation) - will influence the system design from start to finish. Therefore, in determining the performance benefit to be achieved from incorporating an ACT function, careful consideration must be given to the system criticality and associated system complexity/cost.

A flight critical system, designed to have a probability of loss of function less than $1 \times 10^{-9}$ in a 1-hr flight, requires a design approach different from those appropriate for nonflight-critical systems. The elements of the design process are similar, regardless of system criticality, since it is focused on ensuring freedom from errors/faults. The most important aspect of critical systems development is a clear and early statement of the requirements. The system requirements must be specific, they must address philosophical system issues, avoid limiting the design approach, and be clearly communicated to all involved in the design. These issues mean that, for example, early in the design of an ACT system it will be necessary to decide:

- o Whether the system must survive generic faults (Hardware? Software?).
- o How many failures or latent ordinary faults the system must survive?
- o Whether analog will be allowed as a candidate system computer element.
- o What level of integration will be allowed with less critical functions?

## 6.7 SYSTEM DESIGN CONSIDERATIONS

The following observations are based on the Test ACT System experience:

- o The best safety measure is dissimilarity of implementation within the function. This could take the form of analog/digital or dissimilar digital.
- o Analog offers desirable dissimilarity characteristics but does not solve all of the safety issues, and it is extremely difficult to keep the analog elements as simple as desired.
- o Digital implementation offers the potential for comprehensive preflight and inflight test, sophisticated control laws (i.e. mode logic, nonlinear gain schedules). However, it is extremely difficult to <u>prove</u> the implementation is absolutely fault free.
- o Dissimilar hardware and software can provide generic fault protection - but may increase the frequency of false condemnation.
- o Executive monitor design in Critical systems is extremely challenging. It is necessary to achieve the proper balance between the required safety - and undesired nuisance monitor trips.
- o The system design must be just that: a <u>system</u> design. It must simultaneously address all elements of the system: sensors, computers, data transmission, servos/actuators, electric power, and hydraulic power.

## 6.8 ACTUATION

The Test ACT System was originally designed to use four force-summed secondary actuators as the final voting plane between the computers and the elevator power control units. Thus, the redundancy management scheme that was incorporated in the design took advantage of force summing to limit control surface transients resulting from failures, and to allow more time for the monitors to determine the presence of a failure/fault in the channel. These force-summing techniques are well proven and were considered to be a conservative approach in the design of the system. However, force summing does increase the amount of mechanical equipment and complexity that must be included in the control system. There are a number of other approaches to actuation design that offer various attributes. One actuation concept that has been incorporated in certain military airplane applications is the direct drive valve (DDV). The Test ACT System was modified to allow a brief DDV evaluation.

The following observations were made during the limited direct drive valve actuation tests.

- No amount of analysis can substitute for hands-on experience in discovering the potentials and pitfalls of new techology applications, e. g. redundant fly-by-wire direct drive valve actuation.

- In high gain mechanisms, such as those examined in these tests, the experimental results may be dominated by large performance differences due to design details.

- Direct drive valves are attractive as the mechanical summing element for multichannel control systems because they do not involve any null-command internal hydraulic flow.

- Direct drive valves do exhibit a single point jam potential. Whereas a jam in a secondary servo installation would typically be a position command, it would be a rate command in a DDV. For these concepts to be viable for a commercial airplane, these jams would have to be detectable and stoppable to prevent hard-over control deflections.

## 7.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the IAAC Project show there are significant block fuel savings available to a commercial airplane that incorporates active controls technology. Although the magnitude of the benefit is clearly a function of the particular airplane configuration being considered, for a twin engine configuration designed to carry approximately 200 passengers about 2000 nmi, the benefit is between a 6% and a 10% reduction in block fuel. Long-range airplanes with high wing loading, that are primarily maneuver critical with little or no fatigue or flutter material, would appear to benefit from wing load alleviation. All of the configurations examined benefited from the incorporation of pitch axis stability augmentation.

The estimated economics of incorporating ACT indicate that the incremental investment required to acquire an ACT airplane, rather than a conventional airplane designed to operate over the same mission, would yield a return on the incremental investment of 25%. This return is based on a fuel cost of $0.26/liter ($1.00/gal).

The technical impediments that block major applications of ACT stem from the difficulty in achieving a reliable, cost-effective implementation of the ACT functions. The Test and Evaluation phase of the IAAC project addressed these concerns by designing, building, and beginning the testing of a Test ACT System that incorported pitch axis stability augmentation, pitch axis fly-by-wire control, and wing load alleviation. This system was designed to be flight worthy and readily movable from the laboratory to the airplane for flight test.

Following its fabrication, the system was installed in the Boeing Digital Avionics Flight Controls Laboratory for open loop hardware and software tests. Based on the testing that was accomplished, it appears feasible to build ACT systems that meet commericial requirements for reliability and availability. To preclude generic faults resulting in a hazardous condition, such a system would have to incorporate appropriate dissimilarity. Whether analog/digital, as in the Test ACT System, or all digital with hardware/software dissimilarity is open to discussion. There appears to be no fundamental reason(s) that precludes the commercial application of ACT, assuming an appropriate development program is undertaken.

The original Test ACT System used force-summed secondary servos. The final work accomplished on the IAAC Project examined a promising actuation concept that used electric linear force motors to directly move the hydraulic valve that controlled the elevator power control units. Based on the testing that was accomplished with the direct drive valve concept, there is promise of significant simplification possible for fly-by-wire applications, although there is much development work that must be accomplished before they are ready for commercial applications.

The remaining research, included in the basic IAAC Project plan but not completed due to the project termination, is needed to support an industry commitment to incorporate flight critical ACT systems such as those addressed by this project. NASA should continue to sponsor and/or participate in advanced flight control system developments that can contribute to the advancement or maintenance of the world leadership in commercial aviation that the nation currently enjoys. Many of the promising developments that have surfaced in the space programs and/or military programs could potentially benefit commercial aviation. However, in their current state of development the risk of incorporating them into a new airplane exceeds the level of risk that a private company can undertake. NASA's sponsorship could provide the stimulus and financial assistance required to reduce these technical and financial risks to a level consistent with other commercial transport aviation developments. Resumption of that sponsorship is strongly recommended - focused on developments far enough ahead of currently planned and/or commercial systems to allow sufficient calendar time for the NASA program planning/advocacy/funding process.

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| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| NASA CR-3880 | | |

**4. Title and Subtitle**
INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT—PROGRAM REVIEW

**5. Report Date**
March 1986

**6. Performing Organization Code**

**7. Author(s)**
Boeing Commercial Airplane Company,
Preliminary Design Department

**8. Performing Organization Report No.**
D6-52151

**9. Performing Organization Name and Address**
Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, WA 98124

**10. Work Unit No.**

**11. Contract or Grant No.**
NAS1-15325

**12. Sponsoring Agency Name and Address**
National Aeronautics and Space Administration
Washington, DC 20546

**13. Type of Report and Period Covered**
Contractor Report
Oct 1978 to Nov 1984

**14. Sponsoring Agency Code**
505-45-63-06

**15. Supplementary Notes**
Langley Research Center Technical Monitors:
D. B. Middleton and R. V. Hood

**16. Abstract**
This report summarizes the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project, established as one element of the NASA/Boeing Energy Efficient Transport Technology Program. The IAAC Project was undertaken to:

- Produce a credible assessment of the benefits associated with the design of a commercial transport airplane using Active Controls Technology (ACT).
- Identify technical risk areas and recommend test and development programs.
- Implement selected test and development programs.

The performance assessment showed that incorporating ACT into an airplane designed to fly approximately 200 passengers approximately 2,000 nmi could yield block fuel savings from 6% to 10% at the design range. The principal risks associated with incorporating these active control functions into a commercial airplane are those involved with the ACT system implementation. The Test and Evaluation phase of the IAAC Project focused on the design, fabrication, and test of a system that implemented pitch axis fly-by-wire, pitch axis augmentation, and wing load alleviation. The system was built to be flight worthy, and was planned to be experimentally flown on the 757. The system was installed in the Boeing Digital Avionics Flight Controls Laboratory (DAFCL), where open loop hardware and software tests, and a brief examination of a direct drive valve (DDV) actuation concept were accomplished. When it became clear that the project would not continue into a flight test phase, due to funding limitations, the detailed testing of the software necessary to support a flight test was eliminated.

The IAAC Project has shown that ACT can be beneficially incorporated into a commercial transport airplane. Based on the results achieved during the testing phase, there appears to be no fundamental reason(s) that would preclude the commercial application of ACT, assuming an appropriate development effort is included.

**17. Key Words (Suggested by Author(s))**
Energy Efficient Transport, Active Controls Technology, Redundant Automatic Flight Controls, Augmented Stability, Fly-by-Wire, Wing Load Alleviation

**18. Distribution Statement**
[redacted]
Subject Category 05

| 19. Security Classif. (of this report) | 20. Security Classif. (of this page) | 21. No. of Pages | 22. Price |
|---|---|---|---|
| Unclassified | Unclassified | 112 | |

Available: NASA's Industrial Applications Centers